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**GUIDELINES FOR THE DESIGN, ADJUSTMENT
AND OPERATION OF MODELS FOR THE
STUDY OF RIVER SEDIMENTATION PROBLEMS.**

by

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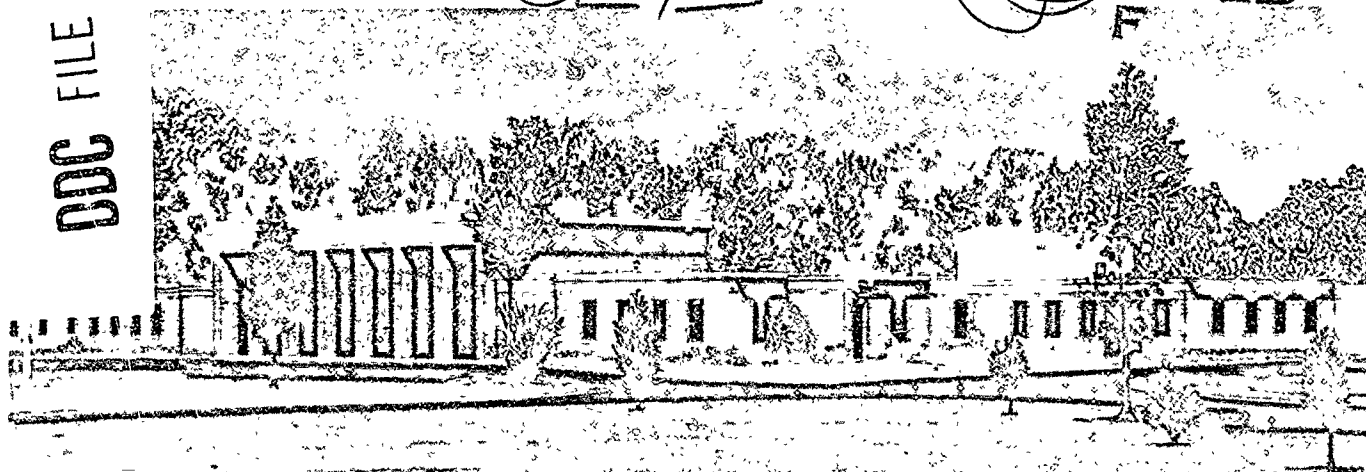
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CONT → effectiveness of various concepts and designs under the same conditions, the development of new principles and procedures or the optimum solution to many problems have to depend to a considerable extent on river model investigations coordinated with results in the field. This report is a general guide for laboratory engineers and technicians concerned with model investigations of sedimentation problems in alluvial streams.

Alluvial streams, whether large or small, have many of the same general characteristics and their development depends on the same basic laws. Movable-bed models used to study river sedimentation problems are essentially small rivers patterned after reaches of larger rivers and are adjusted to reproduce the essential characteristics of those reaches. Engineers experienced with laboratory procedures and the basic laws affecting developments in natural streams can design and adjust models for the study of specific or general problems. → This report describes many of the principles and procedures used in the design, adjustment, and operation of movable-bed models and the factors to be considered in the development of improvement plans and in the interpretation of model results. Appendices cover the characteristics of model bed material, slopes required, and check list for model design and operation.

PREFACE

The report was prepared by Mr. J. J. Franco (retired), former Chief of the Waterways Division of the Hydraulics Laboratory, under special contract with the U. S. Army Engineer Waterways Experiment Station (WES). Preparation of the report was accomplished under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and the general supervision of J. E. Glover, present Chief of the Waterways Division. The draft of this report was reviewed and helpful comments were received from various engineers of WES including Messrs. Glover, J. E. Foster, Chief of the River Regulation Branch, T. J. Pokrefke, Jr., Acting Chief of the Potamology Branch, and by several visiting engineers from foreign countries.

Directors of WES during this study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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GUIDELINES FOR THE DESIGN, ADJUSTMENT, AND OPERATION OF
MODELS FOR THE STUDY OF RIVER SEDIMENTATION PROBLEMS

PART I: INTRODUCTION

River Sedimentation Problems

1. The river engineer is confronted with many problems in sedimentation when dealing with natural or man-made streams having erodible bed and banks. These problems have to be resolved or controlled to some degree if the streams are to be developed, improved, or maintained for navigation and flood control. The protection of adjacent land and structures and the protection and improvement of the local environment and recreation facilities must also be considered in the solution of sedimentation problems. Streams in which sedimentation problems are encountered are generally extremely complex and developments within these streams depend on many factors, most of which are interrelated. Because of the complexity of these streams few basic principles have been developed that can be used by the design engineer in the solution of many river sedimentation problems or in the development of plans for the improvement of troublesome reaches.

2. In spite of the efforts of man and the expenditure of vast sums of money over many centuries, little progress has been made toward a practical solution of many of the problems concerned with the effects of sedimentation. The ASCE Task Committee on Regulation and Stabilization of Rivers published a paper in 1965 entitled, "Channel Stabilization of Alluvial Rivers." This paper summarized information contained in various papers on the subject in the hope that analysis of the data presented would lead to the establishment of certain guides that might improve and advance the profession. The principal conclusion brought out in the paper is that because of the complex nature of alluvial streams, the type of channel regulation and stabilization works used is still a matter of experience and general judgment. Unfortunately, this

conclusion is still essentially correct, and many of the plans and structures adopted have been complete failures or have been ineffective in producing the desired results.

Characteristics of Alluvial Streams

3. Alluvial streams can be characterized by their tendency to meander; irregularity and changing geometry; varying stage, slope, and discharge; and variation in the composition of their bed and banks. Because of the variations mentioned, no two reaches of the same or different streams are exactly the same. The water-sediment ratios of tributaries are never the same as the main stream and can create problems because of their effects on flow conditions and sedimentation processes. Within the stream itself, instability results from erosion of its bed and banks and deposition aggravated by changes in discharge and stage. The riverbed is constantly changing, forming deep and shallow reaches; and the rate of movement of sediment is not constant from one reach to the next.

Sedimentation Studies

4. Considerable research has been conducted on the movement of sediment by many laboratories in this country and abroad. This research has led to a better understanding of the mechanics of sedimentation and to the development of theories involved. Various researchers have developed sedimentation formulas and volumes of literature are available on the subject. Most of the information available on sedimentation is too general to have any practical application in the solution of most river problems. Research and theories developed have been based mostly on the results of flume studies which are two-dimensional and considerably different from natural streams.

5. Some engineers have attempted to develop solutions to sedimentation problems by determining the total sediment load carried by the stream. This information is usually obtained by using various sampling

methods or by computing the sediment load by using one of several sediment transport formulas available or both. The accuracy of measurements would depend on the number of measurements made over a wide range of discharges and would be affected by the difficulty in measuring sediment moving as bed load. Sediment computations are generally based on average conditions of slope and depth and could be in error by a sizable amount because slope is not constant from reach to reach, slope is difficult to measure accurately, and velocity and depth are not uniform across the channel. It must be realized that most of the sediment moving in an alluvial stream continues downstream, and only a small portion of the total load is sufficient to create problems. Even if sediment measurements and computations could be made with a high degree of accuracy and could account for each particle of sediment moving within a given reach of river, a satisfactory method of using this information in the solution of many practical open river problems has not yet been developed.

Need for Model Studies

6. The development and maintenance of streams for navigation and flood control involve considerable construction and maintenance which are expensive. It is important, therefore, that available resources be used with maximum effectiveness. This would indicate the need for continuing research for the development of new and better design principles, construction methods and procedures, and maintenance technique. Some engineers concerned with river problems have felt that the solution to many of the problems should be developed only by experimenting with the river itself. Because of this feeling many problems have never been fully resolved and the trial-and-error approach tempered with experience and general judgment has continued. Experimenting with the river can be expensive and the success or failure of a project generally is not or cannot be fully evaluated because of the difficulty in obtaining adequate data, variations in flow conditions before and after, and differences in channel conditions from reach to reach. The river

engineer is frustrated by the available literature that is too general to be applied in the development of definite solutions to many river problems. Because of the difficulties and costs involved in experimenting with the actual river and the impracticability of comparing the effectiveness of various concepts and designs under the same conditions, the development of new principles and procedures will have to depend to a considerable extent on river model investigations coordinated with the results in the field.

7. The development and improvement of natural streams, particularly for navigation, generally involve the construction of training and regulating structures to improve channel depths and alignment and to stabilize the channel along the selected alignment. The most successful and economical plan for the improvement of a reach of river is that which takes advantage of the natural tendency of the stream. Plans which tend to force the river into an arbitrary alignment, rather than guide it into an alignment that would follow more closely the natural tendencies of the river as indicated by the sedimentation processes affected, will generally require more numerous and more substantial structures with less chance of success. The processes within a river reach cannot always be determined from an analytical study of the data available and the effects of any proposed structures on these processes cannot be predicted with any degree of assurance. Physical model studies can indicate the processes affecting developments and these developments can be observed and measured progressively with flow conditions. Also with model studies various proposed plans can be tested under the same conditions and a comparison made as to their relative effectiveness and amount of construction required. Mathematical models can serve a useful purpose in the analysis of some river problems but cannot replace physical models without considerable refinements and the introduction of the third dimension so important in the development of channel configurations.

PART II: MOVABLE-BED MODELS

Description

8. Models used for the study of river problems involving sedimentation are mostly of the movable-bed type. These models are designed to study problems in specific reaches of an actual stream or to study general problems usually encountered in alluvial streams. Natural streams--whether large or small--flowing in clay, sand, gravel, or even rock have many of the same general characteristics and their development is governed by the same basic laws. Movable-bed models used to study river sedimentation problems are essentially small rivers patterned after a much larger river (prototype) and adjusted to reproduce the characteristics of that river. Engineers experienced in laboratory procedures and the basic laws affecting development in natural streams can design models for the study of specific general problems and adjust them to reproduce the principal factors affecting the development of the channel in the reach under study.

Design Considerations

9. The design of movable-bed models should be based on the nature of the problem or problems to be investigated; the processes involved; solutions being considered or that might be considered; type of information and degree of accuracy required in the results; characteristics of the stream; prototype data available or that could be made available; time available for adjustment, verification, and testing; and other factors such as facilities, personnel, and funds available. The movement of the model bed material in simulation of the movement of sediment in the actual river that affects channel development is a requirement that must be met, if the model is to be used in the study of channel development and sedimentation problems. Therefore, the type of bed material selected for the model will govern to a large extent the scales selected for the model and the design features required to provide the

forces needed to move the bed material based on the characteristics of the prototype stream. In most cases, it will not be practical to construct models with scales large enough to provide the forces required to move material of a practical size and specific weight. The forces needed to obtain the required movement of the bed material are usually obtained by distortion of the linear scales, use of supplementary slope or a combination of both and by increasing the velocity and discharge scale relations. Since these distortions will tend to affect the characteristics of the model stream, their effects on the results should be carefully considered in the selection of the bed material and model scales.

Movable-Bed Materials

Types used

10. Materials most commonly used to reproduce the movable-bed portion of hydraulic river models are sand and crushed coal. Other materials that have been used or considered include pumice, haydite (burnt shale), Bakelite, sawdust, ground walnut shells, and various plastics. Availability and the ease with which material can be handled and controlled under normal operating conditions, in addition to other factors, should be considered in the selection of bed material. The characteristics and advantages and disadvantages of some of these materials are discussed in Appendix A. Combinations of materials or special materials with or without a binding agent have been used to reproduce sections of banks in the model where active caving is occurring in the prototype or where bank caving can be expected from the installation of improvement plans or cutoffs. Generally, the use of an erodible material in model banks is not considered practicable because of the variations in the erodibility and other characteristics of the material affecting bank caving in natural streams and the difficulty of reproducing all of the factors involved with any degree of accuracy even if sufficient prototype data could be made available. When bank caving is a factor during adjustment of the model or in the development of

plans for the stream, its effect can usually be simulated artificially in the model without compromising the ultimate results. The method used should depend on the rate of bank caving to be reproduced and its effects on channel development.

11. Caving banks have been simulated by constructing the fixed portion of the bank in the model to reproduce the ultimate alignment that can be expected during the study or that which would be permitted in the prototype. The portion of the bank between that alignment and the channel is then replaced with a series of movable blocks or bricks designed to maintain a progressive alignment or it is molded in movable-bed material with or without a binder. When some of the blocks are removed to simulate bank caving based on a predetermined alignment or deepening of the channel along the blocks, movable-bed material is added along the bank where the blocks were removed. The amount of material added would be equal to a portion of the volume of the blocks, depending on the composition of the prototype bank and the amount of clay and fine silt that would be moved in suspension. When the amount of bank caving is small, the portion of the bank is molded in movable-bed material without a binder. When a binder is used, the upper portion of the bank (above the elevation of the natural bed) is molded with movable-bed material with a binder such as plaster of paris or mason plaster with the fibers removed. The amount of binding material used should be such that the bank will be more resistant to erosion under the velocities and forces encountered in the model than those indicated by prototype surveys or that can be anticipated. The bank can then be scraped with a trowel to control the alignment or rate of bank recession as indicated by the depth of scour or undermining of the bank.

Grain size

12. The grain size of the model bed material usually cannot be reduced to the scales of the model. Some scientists and engineers consider this as a distortion which affects the degree of similarity that can be obtained between model and prototype. As mentioned previously, models of rivers are small rivers patterned after larger rivers and adjusted to reproduce the characteristics of the larger rivers.

In natural streams, the size of bed material does not vary in direct proportion to the size of the river and tends to be larger in the smaller streams. Since the same general laws apply to rivers whether large or small and whether moving in sand, gravel, or clay, the size of the material forming the channel bed should not in itself affect channel development.

13. The larger grain sizes require greater forces to be moved and could affect the type of movement, particularly in models. Material in the low range of sizes will tend to ripple within the model velocity range; ripples also can be observed in streams such as the Mississippi River. Ripples have little effect on roughness in large streams since their size in relation to depth is small. However, in models these ripples can be large in comparison with the depths and when converted to prototype dimensions can be quite large in comparison with the depth and cross-sectional area. Rippling of the bed material is a function of grain size, current velocity, and temperature of the water. Fine material including sand used in movable-bed models will ripple at all natural water temperatures but some sizes will ripple at lower temperatures and will not ripple at the higher temperatures. Larger grain sizes will tend to form sand waves or dunes that move progressively downstream with normal velocities. Besides its effect on bed form, larger grain sizes require greater tractive force and velocity to be moved and thereby affect the velocity scale and slope of movable-bed models.

Laboratory Practices

14. During its existence, the U. S. Army Engineer Waterways Experiment Station (WES) has conducted movable-bed type model studies of many different streams, reproducing various lengths of reaches. These studies have been concerned with a wide variety of problems and have been carried out on models of different linear scales and degrees of distortion and with various types of bed materials including sawdust. Experience gained during these studies and observation of practices at other laboratories indicate the techniques used at WES to be the best

and most practical for the study of the various types of problems. Many laboratories operate models of natural streams with one flow referred to as the "dominant" discharge. Operating with one flow would simplify operation of the model and permit the use of more automatic controls, including the feeding of the bed material. Since most problems in alluvial streams result from changes in river stages and discharge, it would be extremely difficult, if not impossible, to develop the optimum solution to many channel development and maintenance problems using a constant flow.

PART III: DESIGN OF MODELS

Prototype Data

15. The prototype data required to undertake a movable-bed model study vary with the type or types of problems to be investigated and the general characteristics of the reach of river to be studied. The basic data required include the following:

- a. A complete recent up-to-date hydrographic survey of the channel bed showing the elevation and alignment of the top of bank. Surveys made prior to the date of the latest survey would be helpful in evaluating developments in the prototype stream and would be required as a basis for verification of the model.
- b. Elevation of adjacent overbank areas subject to overbank flow.
- c. Horizontal control grid that would permit a tie-in between channel and overbank surveys, surveys made during different periods, and location of structures affecting flow.
- d. Location, dimensions, and elevation of training and stabilization structures and date of construction, if available.
- e. Dredging performed during the year preceding the latest channel survey including purpose, area dredged, quantity, disposal area, and dates.
- f. Location of active bank caving, if any.
- g. Location and elevation of any bedrock or gravel bars that could affect channel development.
- h. Water-surface elevations or slope profiles and stage-discharge relation for the reach.
- i. Flow hydrograph for at least a year preceding the date of the latest survey or for the period between that survey and a preceding survey if longer than one year.

16. Additional data that would be helpful and should be furnished, if available, include:

- a. Latest aerial photographs of the reach and photographs of special facilities such as river structures and docking and mooring facilities.
- b. Local surveys or surveys made before or after dredging within the past year or two.

- c. Recent history of the reach even if based on general observations.
- d. Stage-duration curves.
- e. Sediment-discharge transport curves.
- f. Current directions and velocity observations showing date taken and type of equipment used in making the observations.
- g. Plans being considered for improvement of the reach.

Evaluation of Field Data

17. An evaluation of the prototype hydrographic survey or surveys should be made before design of the model is finalized. This evaluation should also determine when the survey was made with respect to the flow hydrograph. A survey made at the end of a high-water period will tend to show the channel deeper in bends and shallower in crossings than a survey made at the end of a long low-water period. If the model entrance or exit is to be in a bend, the fixed apron should be such that it can reflect the changes that can be expected with changes in flow conditions. If two surveys are available, the fixed portion of the entrance and exit apron should be at least as low as the lowest elevation of either of the two surveys. The shape of the cross section of the fixed apron should also reflect the changes that could be caused by changes in flow conditions from that which occurred prior to the time of the survey to which the model is molded and by the alignment of the channel upstream and downstream of the model limits.

18. Water-surface elevations available from the prototype should be plotted for representative flows and the slope profiles studied to determine the slope in feet per mile and changes in slope within the model reach. This information should be helpful in determining supplementary slope required, and the profiles should be preserved for use during operation of the model. Water-surface elevations should also be used to determine the extent of flow along the overbank, the probable effects of this flow on channel development, and the problem to be studied in particular.

19. Structures should be listed as to type, when constructed, dimensions, and general condition. Training structures or any structures that could affect channel development constructed during the verification period should be installed at the appropriate time during operation of the model. If intermediate surveys are available they should be used to determine the effects of structures on channel development.

20. An analytical evaluation of the recent history of the reach including flow conditions, changes in the bank lines, and the nature of the problem should be made and recorded. The record should include the important developments that have to be reproduced in the model, the type of remedial or improvement plans proposed, and alternate solutions that might be required or should be considered. This information should be kept in mind in designing the model to provide for possible future changes required in the test of improvement plans and would be helpful in the adjustment of the model.

Model Limits

21. Model limits should first be based on the evaluation of factors and flow conditions affecting the problem in the prototype and the extent and nature of any overbank flow that might contribute to developments within the reach. Also to be considered in the selection of model limits are proposed plans or plans that might be considered for the improvement of the reach and the probable effects of these plans on flow conditions. The upper and lower limits of the model are particularly important since they could affect flow conditions into and out of the model. The ideal locations for the upper and lower limits would be in a relatively straight reach that is reasonably stable and not affected appreciably by changes in stages and discharges. There are really no such ideal conditions in alluvial streams. Location of the limits in a bend would usually provide a stable bank on the concave side that could be used with some adjustment in the alignment of currents to compensate for the direction of flow from upstream. A

disadvantage of this location is that the movement of sediment varies with scouring and heavy movement during high flows, and with deposition and little movement during low flows. If this location is selected, the movement of sediment should be considered. In straight reaches the channel will tend to meander and currents will vary as to alignment and velocities. Overbank areas to be considered are those where there is flow along the overbank, part of which either leaves the channel or returns to the channel within the limits of the model. Flow along the overbank that does not affect flow within the channel need not be reproduced unless it will be affected by proposed plans. If areas with flow along the overbank are not reproduced in the model, because these areas bypass the modeled reach, some compensation must be made in the discharge introduced.

22. Further adjustments in the model limits are then made on the basis of the model scales needed for the study and the space available. It is often necessary to compromise between model limit and model scales; this should only be accepted when the effect of such compromise will not seriously affect the results of the study. Usually there are some adjustments that can be made to compensate for the effect of flow that cannot be reproduced naturally in the model because of reduction of area reproduced or reduction in model scales. When all of the important factors affecting development within the channel cannot be reproduced naturally, adjustment of the model becomes more involved and could require considerably more time and effort and possibly some modification in normal operational procedure or compensating facilities. It is important, therefore, that the limits be selected first on the basis of what is needed for the study and trimmed only after carefully considering the effects on the study and the facilities available.

Model Distortion

23. Principal considerations in the design of movable-bed models should be that the hydraulic forces developed be sufficient to move the material forming the channel bed in simulation of the sediment movement

in the prototype and that the model be capable of defining the problem. The horizontal scales that would result in a practical size model based on operation, space, and cost are usually too small to provide the hydraulic forces sufficient to move material of a practical size and specific weight; therefore these forces are obtained by distortion of the linear scales and/or supplementary slope (the slope needed in addition to that resulting from the linear scales to produce adequate movement of the bed material used) and exaggeration of the discharge and velocity scale relations. Distortion of the linear scales involves the use of a vertical scale ratio larger than the horizontal scale ratio, thus providing greater model depths and slopes. Supplementary slope provides a tilt to the model in addition to that resulting from the linear scales, thus increasing the total model slope by the amount of the supplementary slope; this permits the use of a larger discharge scale ratio than the theoretical based on the linear scales.

24. Supplementary slope with the exaggerated discharge scale ratio and distortion of the linear scales tend to affect the relation of velocity, width-depth ratio of the channel, and flow around bends and into side channels and consequently tend to affect the distribution of energy within the channel and the meandering characteristics of the model stream. Also, distortion produces changes in the slopes of the banks and in the size and shape of certain structures and formations within the channel that could affect local flow conditions and channel development. Because of the effects of model distortion, distortion of the linear scales should be as small as conditions will permit. Use of higher distortion in model linear scales will reduce the initial cost of model construction and space required but will usually increase the time and cost of model adjustment and if not properly handled could have some adverse effects on model results.

25. The effects of distortion can be minimized to some extent by modification of structures and in some cases modification of slopes of riverbanks. Rock dikes usually cannot be constructed with slopes that would result from use of horizontal and vertical scale ratios, particularly when the degree of distortion is relatively large, unless

constructed of concrete or fabricated with metal. Also with a distorted scale, use of the actual vertical and horizontal scales would produce a relatively steep nose on the dike that would cause excessive scour and turbulence. In such cases it is better to compromise by using an undistorted slope on the ends; this is accomplished by extending the toe and shortening the crest to compensate for the effect of changes in length. However, when such action is taken the length of the dike shown on the plan should be based on what it would have been without the adjustment. Similarly, it would be helpful in some cases to reduce the slope of steep bank by moving the toe of the slope riverward and the top of bank landward the same amount. In the case of a dam or spillway with a stilling basin, the usual practice has been to construct the dam and stilling basin with the horizontal dimensions in the direction of flow based on the vertical scale. This will not be theoretically correct but will provide better action within the stilling basin with all flows and should be adequate for the type of tests and results that can be expected from these models. Use of a distorted scale on structures of this type could change its shape to such an extent that it would no longer function as designed.

Supplementary Slope

26. Supplementary slope will be required in most movable-bed models of rivers to develop the forces required to move the bed material. Supplementary slope is the slope needed in addition to that resulting from the linear scales to produce adequate movement of the bed material used and should be incorporated in the design of the model. The slope resulting from the linear scales will equal the prototype slope multiplied by the degree of distortion, assuming that the vertical scale is larger than the horizontal scale which is usually the case with most models. Slopes needed will vary with the size and type of stream reproduced and the amount of sediment movement in the stream. The total slope used to move fine sand (0.2-mm medium grain size) in movable-bed models at WES has been about 0.00065 to 0.0010, depending on the

characteristics of the stream being reproduced and the linear scales used. The rate of bed movement will also vary to some extent with the temperature of the water and channel depth (vertical scale). Most of the coal-bed models at WES have been adjusted with a total slope of about 0.00030 to 0.00050; these slopes are substantially less than those indicated by flume studies. Movement of sediment in a sinuous channel is considerably different from that in a straight channel because of the difference in the distribution of velocities across the channel and the degree of turbulence affecting scour and shoaling.

27. To determine the amount of supplementary slope required, if any, it is necessary to first determine the slope in the prototype multiplied by the scale distortion. The supplementary slope is then equal to the total slope required in the model for the bed material used, minus the slope of the prototype, and multiplied by the degree of distortion. In other words:

$$S_s = S_m - \left(S_p \times \frac{d_r}{l_r} \right)$$

where

S_s = supplementary slope

S_m = total model slope required for the bed material

S_p = prototype slope

d_r = vertical scale ratio

l_r = linear scale ratio

supplementary slope determined by this method should be the average and should be checked with that used on models of similar streams. Consideration should also be given to modification of the supplementary slope based on the characteristics of the channel from reach to reach. Some adjustments can be made in supplementary slope after construction of the model based on the results obtained during the adjustment tests.

28. An important factor which should be considered in determining the amount of supplementary slope required is that distortion of the linear scales affects differently the flow characteristics of reaches of a stream having different width-depth ratios. This is because the

hydraulic-radius scale ratio is not the same for narrow deep channels as for wide shallow channels of the same cross-sectional areas. In order to maintain the same velocity scale relation through reaches of different width-depth ratios, the supplementary slope required in wide shallow reaches has to be greater than for deep reaches of the same cross-sectional area. The difference in slope required would depend on the amount of linear scale distortion and the difference in width-depth ratios of the various reaches, which could be substantial. The difference can be approximated by determining the hydraulic-radius scale ratio of a typical cross section in each reach and determining the slope required to maintain the same velocity scale ratio in each section. Based on Manning's formula, $V = 1.486 R^{2/3} S^{1/2} / n$ and proportional to $R^{2/3} S^{1/2}$ assuming that the roughness is the same where

V = average velocity in cross section

R = hydraulic radius

S = slope

n = roughness factor

Using subscript n for narrow section and subscript w for the wide section, $R_n^{2/3} S_n^{1/2}$ should equal $R_w^{2/3} S_w^{1/2}$ if the velocity scale ratio is to be maintained the same in both types of sections or $S_w = (R_n^{4/3} / R_w^{4/3}) S_n$. Assuming a model with horizontal scale of 1:500 and vertical scale of 1:100 having a narrow channel 2500 ft wide and an average depth of 20 ft, and a wide channel 5000 ft wide and an average depth of 10 ft, the slope required in the wide shallow section would be 2.48 times the slope in the narrow section to maintain the same velocity scale, model to prototype, in both sections. The illustration is used to indicate that the difference in slope required can be considerable in distorted models of some streams.

29. The differences in the slopes required indicate the need for differences in supplementary slopes from reach to reach to compensate for the effect of distortion of the linear scale and will vary from low to high stages. The question is, what happens if the additional slope is not provided? Since the wide section is less efficient than the

narrow section, a backwater effect is developed that raises stages near the upper end of the wide section, producing a steeper slope in the wide shallow reach and a flatter slope in the narrow deep section upstream, particularly during the lower flows. This difference is vividly demonstrated by model slope profiles plotted from gage readings adjusted for supplementary slope, particularly during lower flows. In many cases, these plots will show steep water-surface slopes in some reaches and flat or negative slopes in others. This effect is also noticeable in the movement of bed material, particularly near the model entrance and exit where material is introduced and extruded. If the supplementary slope provided in a given reach is more than that required for the flow reproduced the water-surface slope will tend to be less, since the water-surface elevation at the upper end of the reach will tend to be lower.

30. The difference in the supplementary slope required has more or less been ignored in the design of most models, but in some cases adjustments have been made in the rails used for molding and sounding of the bed. The adjustment in supplementary slope normally would be required only in the channel since the effects decrease with an increase in discharge and river stages. Where different supplementary slopes are indicated by differences in channel cross section, the average required for the channel should be incorporated in the fixed banks and overbanks during design of the model. The model will tend to adjust the bed when operated to stability; but this adjustment, if appreciable, cannot be accomplished during reproduction of the verification hydrograph when it is based on a relatively short period. Although the bed tends to adjust its slope, unless the rails are also adjusted there will be a difference in the true bed elevation and that indicated by sounding from the unadjusted rails.

Model Entrance and Exit

31. Design of the model entrance and exit can be an important factor in the adjustment and verification of the model. The entrance to

the model which includes the headbay and fixed apron should be based on the proper distribution of flow entering the model and changes that can be expected with varying discharges. The entrance apron should be a fixed reach of the channel to get the flow started correctly and designed to permit the reproduction of the effects of the channel upstream of the model limits on flow distribution and the changes that can be expected with different flows. The length of the fixed channel will vary from 3 to 4 ft to more than 10 ft depending on model scales, conditions upstream of the model limits, and location of the upper end of the model with respect to channel configuration. The apron should be constructed of 1/2- to 1-1/2-in. gravel or crushed rock except for a short section near the entrance pit which should be of concrete and streamlined to provide a smooth entrance of water from the pit to the model.

32. The cross section of the approach channel (apron) should be based on the available surveys and modified based on changes that can be expected to result from changes in flow conditions. For instance, if the upper model limit is in a bend and the only survey available was made at the end of a low-water period, the channel can be expected to be deeper during high-water periods and the apron should provide for the deepening of the channel. In a crossing or straight reach the channel would tend to be deeper at the end of a low-water period than at the end of a high-water period and some changes in the alignment of the currents can be expected with changes in discharge. When placing the fixed part of the apron lower than that indicated by the prototype survey, the bed should be molded with movable-bed material to the cross section indicated by the survey to which the remainder of the model is molded. Similar considerations should be given to the exit apron as it could affect channel developments upstream.

33. The entrance pit should be designed to provide for the proper distribution of flow into the model and would depend on the discharge range required for model operation, amount of overbank flow on each side of the channel, and method of introducing flow into the pit. In order for the model entrance to have the most control of the

distribution of flow, it is important that the velocity of flow approaching the model be low with a minimum amount of turbulence and fluctuation. At least one baffle wall will usually be required between the model and the water supply outlet unless the pit is unusually large and deep.

34. The outflow pit is also important since it is necessary that the material extruded from the model be trapped and not permitted to be carried over the tailgate. In this case, the pit should be deep enough and long enough to permit the settling of movable-bed material. Unusually small tailgates (substantially narrower than width of channel) should be avoided. With coal-bed models, baffles will be required between the end of the model and the tailgate with the upper portion of at least one of the baffles impermeable for some 4 in. to 1 ft below low water depending on the size of the pit, width of tailgate, and discharge range. This arrangement would cause flow from the model to move downward and disperse before passing over the tailgate.

Slope

35. Slope is one of the best indicators of flow conditions and sediment movement along the river channel. Unfortunately, it is a difficult parameter to measure with any degree of accuracy in the prototype, particularly with rivers having relatively flat slopes, and sufficient data covering short reaches are seldom available. Prototype slopes have to be considered in the design of the model and in the selection of the required supplementary slope. Generally, problem reaches have some temporary gages established and read periodically, particularly during surveys of the channel, since the information is needed to convert water depths to elevations.

36. Any water-surface elevations available should be used to develop water-surface profiles for representative flows from low to high. These profiles should be plotted and studied to determine if there are any significant differences from one reach to another or from high to low flows. These profiles should be kept for use during adjustment of

the model and should be used to determine water-surface elevations at the model control gage for flows to be reproduced.

37. In adjusting the model it should be considered that the primary objective is to obtain a set of conditions that would reproduce developments in the channel bed similar to those that have occurred and could be expected to occur in the river under the same conditions. Meeting the primary objective will not necessarily develop slopes in the model that are close reproductions of the prototype slopes because of the variation in discharge scales required and variations in hydraulic-radius scale ratio with stages in channels of different width-depth ratio.

PART IV: ADJUSTMENT AND VERIFICATION

Principle of Verification

38. Before a movable-bed model can be used to test the effectiveness of proposed improvement plans, its ability to reproduce conditions similar to those that can be expected in the prototype must be demonstrated. Complete similarity between the model and its prototype can seldom be obtained because of the inherent distortions incorporated in model design and in the operation of the model. Because of the various dissimilarities, the degree of reliability of this type of model cannot be fully established by mathematical analysis and must be based on the model verification. Verification of the model involves the adjustment of various hydraulic forces, time scale, rate of introducing bed material, and model operating technique until it reproduces with acceptable accuracy the changes known to have occurred in the prototype during a given period. Before the verification of the model can be accepted, the reproduction of the problems to be resolved and the effect of any differences between the model and prototype on the probable solution should be considered. The successful verification would establish the various scale relations, model operating procedure, and degree of similitude that can be expected.

Factors Affecting Model Verification

39. As mentioned previously, model verification involves the adjustment of the model and the forces affecting development until the model has demonstrated its capability of reproducing conditions generally similar to those that have occurred in the prototype. The conditions in the prototype have to be based on observations, hydrographic surveys, photographs (particularly aerial photographs), borings and special measurements, and computations. Sufficient data are seldom, if ever, available and time required for adjustment can be affected to a considerable extent by the adequacy of the data. Ideally, information

needed should include the amount and type of changes that have occurred during a given period, the man-made changes that could have affected some of the changes, composition of the bed including gravel deposits, remnants of old structures, and flow conditions during the period of change.

40. Adjustment of a model involves a knowledge of the factors affecting development within a stream, analysis of the characteristics of the reach under study, careful observation and analysis of developments within the model, evaluation of the factors that could be affecting developments, and use of engineering judgment and experience in the application of the type and degree of adjustments. The degree of similitude attainable and the time required for model verification depend upon the characteristics of the stream; amount and type of prototype data available; scales of the model; experience and knowledge of river sedimentation processes applied to the design, operation, and adjustment of the model; and the refinements to which the adjustment of the model is carried.

Verification hydrograph

41. The flow hydrograph affects developments within the prototype stream and will affect developments within the model. It is important, therefore, that the verification hydrograph be such that it will control developments within the model. If two surveys are available covering a reasonable period of time (at least one year), the model should be molded to the earlier survey and operated by reproducing the hydrograph recorded in the prototype during the period between the two surveys. If the period between the two surveys is relatively short, the hydrograph should be started with the data recorded a sufficient time before the date of the earlier survey to include at least a year of operation. When only one survey is available, the model bed for the adjustment should be molded to that survey and the model operated by reproducing the hydrograph recorded in the prototype for at least a year preceding the date of the survey. If the hydrograph is too short or the movement of the bed material is not adequate, the bed of the model will not

change sufficiently to indicate whether or not the model is reproducing prototype conditions.

42. The hydrograph used should be plotted on graph paper delineated in months and days, and then blocked off into a series of constant stages (Figure 1). Efforts should be made to avoid stages having a duration of less than about 30 minutes based on the model time scale. A careful study of the hydrograph could provide for the combining of peaks and valleys of short duration into one or more stages. Such combinations should consider the effects of the peaks and valleys between peaks on channel development, particularly as they could affect the problem to be studied. Many laboratories conduct studies of river problems by reproducing one flow considered to be the "dominant discharge." It is the opinion of experimenters at those laboratories that this is the discharge that affects and controls the development of the channel configuration. Although use of one flow would simplify operation of the model and reduce time required to reach stability, it is definitely not recommended for the study of most problems encountered in the development and maintenance of natural streams, particularly for navigation.

Discharge scale relation

43. In a movable-bed model, the discharge scale relation must be such that the movement of model bed material is generally similar to the movement of sediment in the prototype for the range of flows included in the hydrograph. The discharge relation depends on the model linear scales and on the type of bed material used. Models for the study of problems in large streams are generally too small to develop the forces required to move the bed material normally used in models of this type, particularly during the lower flows. Therefore the additional forces required are provided by use of discharge scale relations that are larger than those indicated by the theoretical scale based on the model linear scales.

44. In selecting a discharge scale relation it must be considered that the model will be operating very near the critical tractive force or critical velocity required to start movement of the material and that the prototype is operating considerably above that range. The

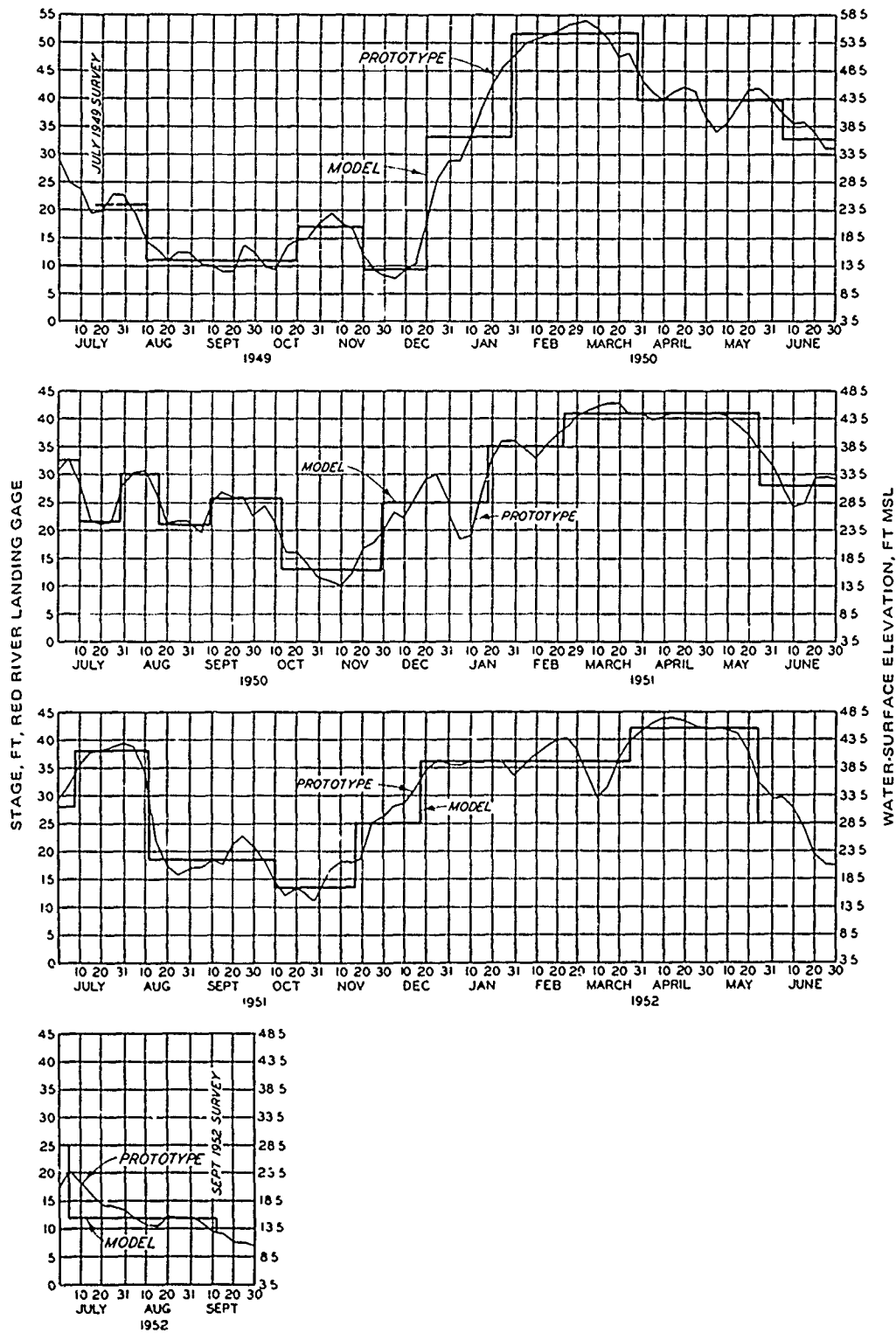


Figure 1. Stage hydrograph, verification test

tractive force developed near the critical velocity for a given material increases as a curve and then becomes a relatively straight line.*

Since the model is operating in the curved range and the prototype in the high or relatively straight range, the model discharge scale has to be variable to provide the same relation of movement of sediment in the model that occurs in the prototype for the range of flows reproduced.

45. The best method of selecting a discharge scale relation is to base it on previous experience with models having the same type of bed material and reproducing rivers of the same general characteristics. If the linear scales are not the same, adjustments can be made based on the differences in the vertical and horizontal scales and maintaining the same velocity scale ratios as in the previous models for comparable flows. A discharge scale that is not substantially larger for the lower flows than the higher flows will tend to have the deep portions of the channel too deep and the shallow portions (particularly crossings) too shallow, assuming that other conditions are reasonably correct.

Preparation of Model Data

46. After completion of the basic design of the model and during actual model construction, data should be prepared and made available for use in molding of the model bed and for comparison with developments in the model during the adjustment and verification. These data should include the following:

- a. Master sheet. A master sheet should be prepared for recording model data such as bed soundings, improvement plans, and other information as might be obtained from the model such as current directions, velocities, and scour and fill areas. The sheet should contain all of the general information that would be common for the study and be in such form and size that it can be reduced to standard report size. Standards for preparing these sheets are available to the draftmen at WES.
- b. Prototype surveys. Using the master sheet, a map showing

* U. S. Army Engineer Waterways Experiment Station, CE, "Studies of River Bed Materials and Their Movement, with Special Reference to the Lower Mississippi River," Paper 17, Jan 1935, Vicksburg, Miss.

the prototype bed configuration to which the model is to be molded for the start of the adjustment test and one for the verification condition to be reproduced in the adjustment (if different from the start of the adjustment) should be prepared. This sheet should include at least the controlling elevations on each sounding range in addition to contours.

- c. Slope profiles. Prototype slope profiles should be plotted for representative flows from low to high based on available prototype data. These profiles should be plotted on a sufficiently large scale to permit their use in comparing model data with prototype data. The profiles should be selective to cover the range of flows and variations that might be caused by backwater effects or to the rate and direction of change in discharge. It should be considered that if the prototype data are not sufficiently detailed, the differences in the slope from reach to reach, which can be considerable particularly during low flows, will not be indicated.
- d. Control gage. A gage should be selected near the center of the model or center of the problem area for use as a control gage during initial operation of the model. If prototype data are not available for that gage, a gage-relation or stage-discharge relation curve should be developed for that gage. In establishing a stage-discharge relation, it should be considered that the relation for a fast rising and fast falling stage can be sufficiently different to affect channel development.
- e. Discharge scale relation. A preliminary model-to-prototype discharge relation curve based on the best information available and experience with similar models should be developed as discussed in paragraph 45 for use during the initial operation. The discharge scale ratio usually varies with river stage but in cases where there are wide variations in discharge with stage, it is better to develop the discharge scale relation based on prototype discharge. When slope and stages vary considerably for the same discharge due to backwater effects, some additional adjustment might be required based on slope to the one-half power. The discharge relation is usually plotted as a curve on semilog graph paper as shown in Figures 2 and 3. The final curve used will depend on the requirements for model adjustment.
- f. Sediment relation. A preliminary model sediment-discharge curve should be developed based on experience with similar models and modified based on differences in model scales and size of river. Typical sediment discharge curves are shown in Figures 4 and 5. There will be some

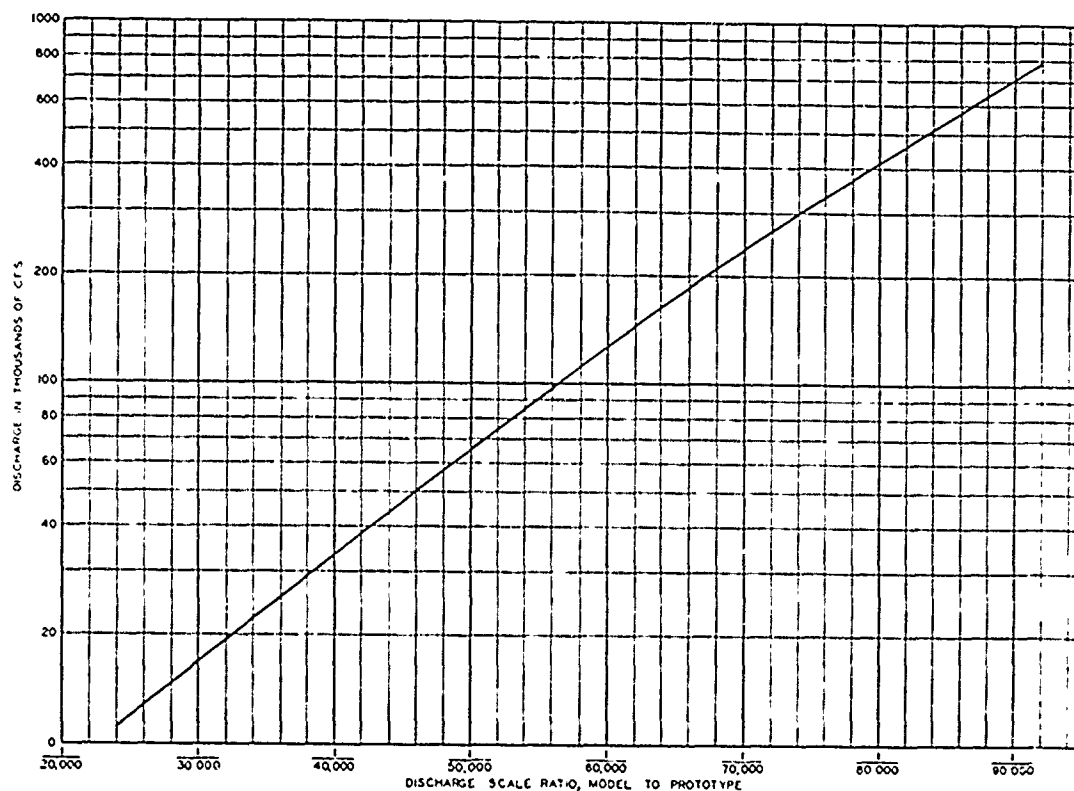


Figure 2. Coal-bed model, discharge relation curve,
scale 1:120-1:80

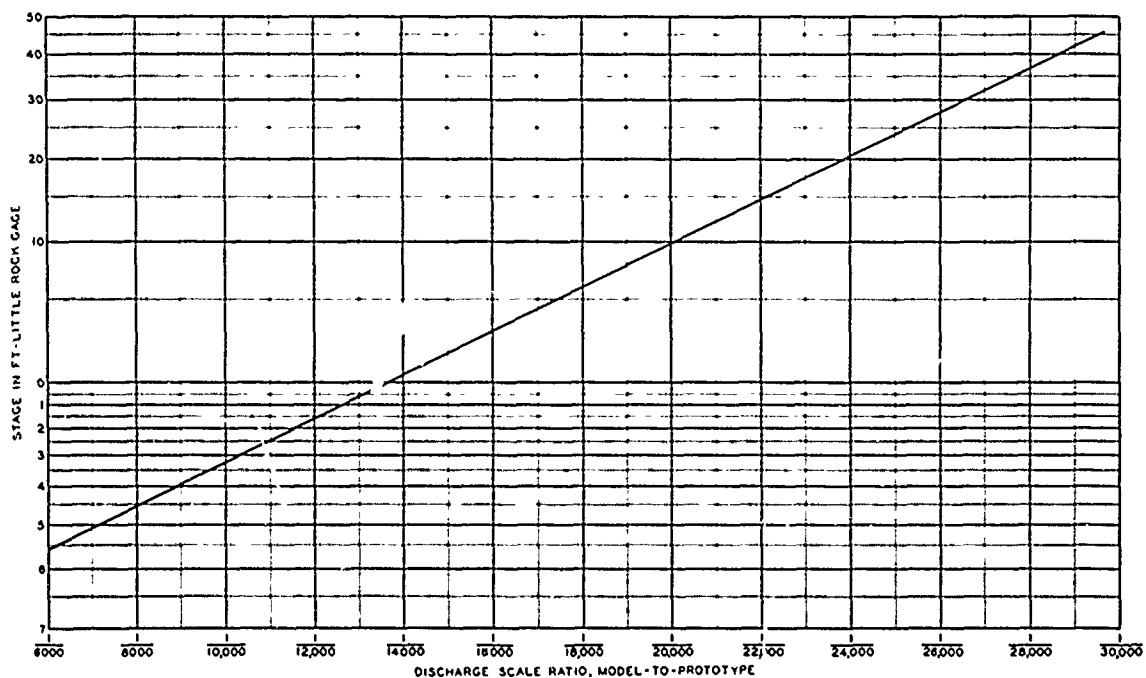


Figure 3. Sand-bed model, discharge relation curve,
scale 1:250-1:36

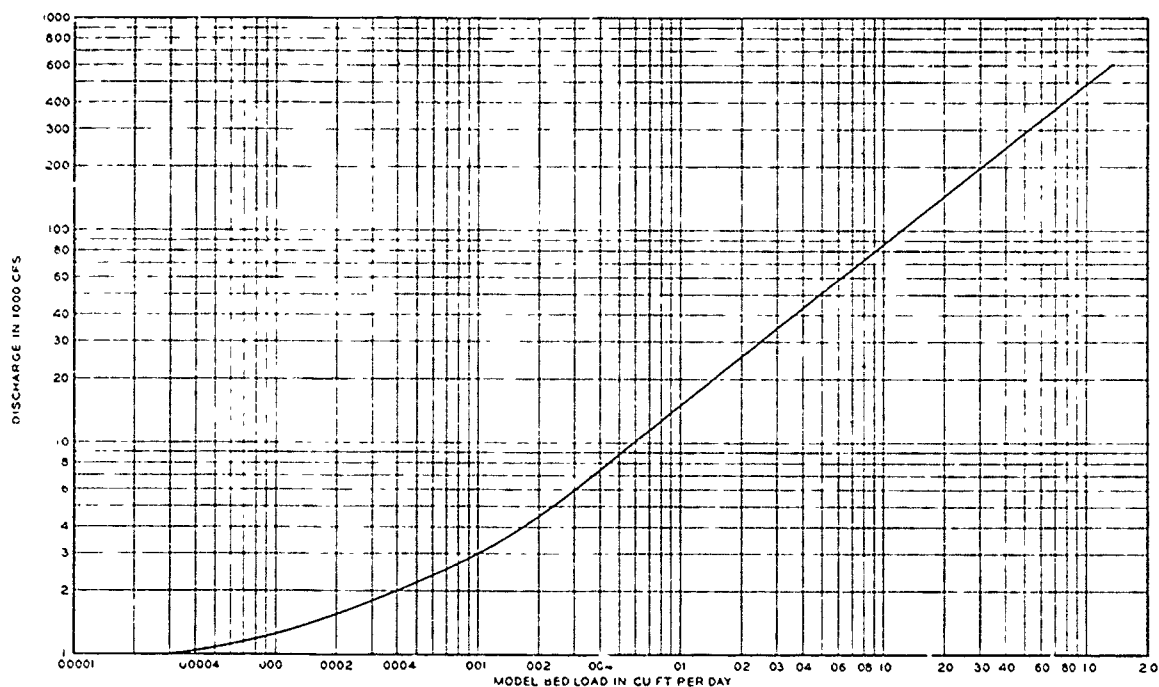


Figure 4. Coal-bed model, discharge versus bed load,
scale 1:120-1:80

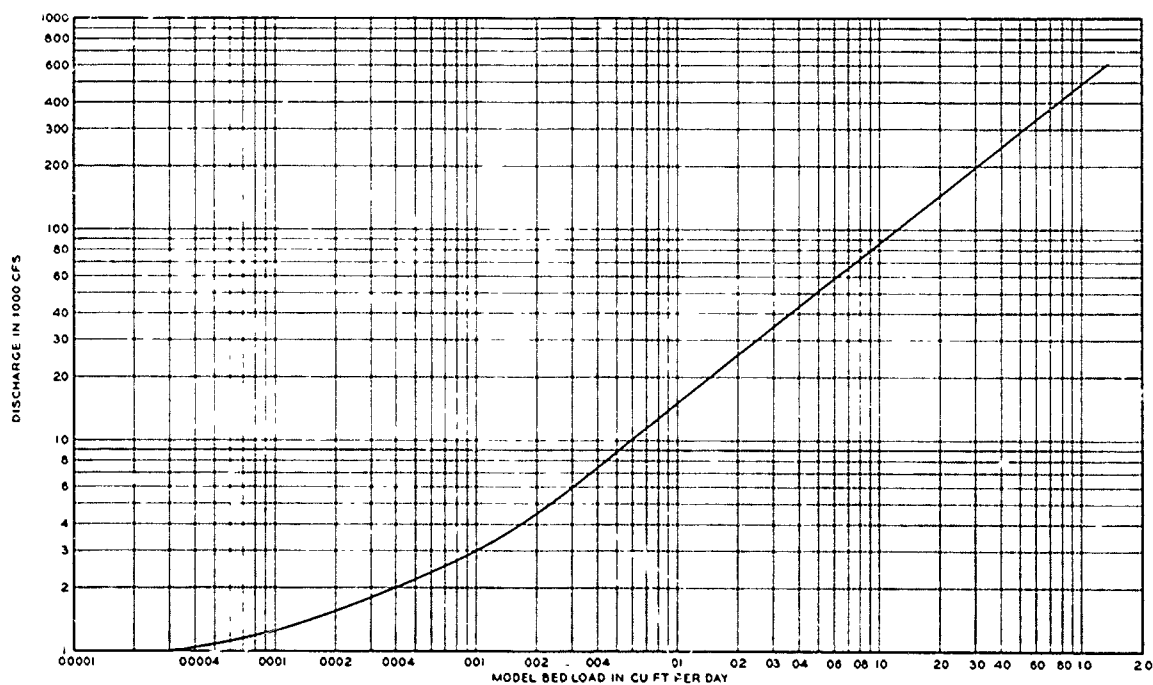


Figure 5. Sand-bed model, discharge versus bed load,
scale 1:250-1:36

variations due to channel geometry near the model entrance and requirements for model adjustments.

- g. Operation data for representative flows. Several flows should be selected that are considered representative of the range of flows to be reproduced in the model study for use in the preliminary and subsequent adjustment of the model. These flows should include at least a low flow (near mean low water), a midbank flow, and a bank-full flow. Operation data for each of these flows should be prepared based on the preliminary data and scale relations developed. These data should include stage or water-surface elevation at the control gage based on model gage zero, model discharge for each stage, and notes as to the type of sediment movement that should be expected for each flow.

Preparation of Model

47. Before operation of the model can be undertaken, the bed will have to be molded to conform with the survey selected for the start of the adjustment tests. The aprons at the model entrance and exit should be fixed with crushed rock or gravel as mentioned previously. The movable-bed material whether coal or sand should be clean and sufficiently damp to permit compaction and shaping during molding. Loose dry sand can create problems since it is difficult to compact and pockets of quicksand can form when wet. If new coal is used as bed material, it should be washed thoroughly to eliminate dust and fine material that discolor the water. Even after washing through a screen, it would be advisable to run water through the model while turning the coal over with shovels until there is little discoloration of the water. Coal that is not washed thoroughly will tend to form lumps of fine material and crust that can affect its movement and channel development. Any lumps noted in the bed during operation should be removed.

48. Molding of the model bed should be accomplished under close supervision. The supervisor of the molding operation should have a map available and use it to check the shape and alignment of the channel and bars particularly between templates. Since an improperly molded bed can seriously affect results, the elevation of the bed between templates

should be carefully checked and the name of the checker indicated on the operation data sheet. Observation of the model during flooding should indicate any discrepancies or irregularities in the molded bed that might have been overlooked. The bed of the model should be kept damp during flooding and deep portions of the channels filled separately to prevent unnatural erosion before flooding is completed.

49. After the model is flooded the zero of the model gages, initially set with a level based on the bench mark elevation, and elevation of the rails with respect to the gages should be checked. The gages should be checked with a level pool to determine if all of the gages are reading the same insofar as the pool is concerned. The model curb rails should be checked with respect to the water-surface elevation of the level pool as to their elevations and any supplementary slope provided in the rails. The elevation of the level pool as obtained by measurements from the sounding rail should indicate the amount of supplementary slope provided. The approximate elevation of the pool from the sounding rail could be measured with the sounding stick or more accurately with a movable gage mounted on the sounding rail. Errors in the curb rail elevation can produce differences in the molding of the bed and in the results of tests (soundings) that might be blamed on operating procedures and could cause considerable frustration in attempting to adjust for the difference. Another item that should be checked is the size of the venturi meter, weir, or other discharge measuring device that might be used and the calibration or rating curve for the device used. Each step in checking the model should be recorded with the date, results, corrections (if any), and individual responsible. Eliminating any possible errors before starting operation could save considerable time and money and could result in a better and more reasonable adjustment.

Preliminary Adjustment

50. In the first step toward adjustment of the model, considerable time and effort can be saved by making preliminary runs with the representative flows selected. There would be no point in attempting to

reproduce the verification hydrograph until there is some assurance that the discharge scale is reasonably correct and that movement of the bed material at least appears to be satisfactory for the range of flows to be reproduced with the hydrograph. Each of the flows selected should be operated and adjusted until movement of bed material for that flow appears to be reasonable, based on experience and judgment. If sand is used as the bed material, operation should be started with a high flow to permit the bed to form ripples.

51. During operation of the model, flow entering the model should be observed to determine the adequacy of the entrance pit and the effectiveness of the baffles in providing satisfactory flow distribution. Some of the adjustments indicated could be made during the operation and the effects noted. Observations should also be made at the lower end of the model to determine the adequacy of exit conditions, particularly as to whether or not there is any unnatural scour caused by improper transition between the movable bed and fixed apron. It is also important during the initial runs to maintain the water level in the model at least as high as the stage for that flow while the discharge is being increased to the required amount to prevent any unnatural or excessive scour in the event that the discharge scale ratio is too large. By gradually increasing the discharge to the required amount and then lowering the water level to the correct elevation, the effect on channel bed can be observed and operation could be discontinued before the bed is disturbed excessively. Molding of the model bed is an expensive and time-consuming operation and should be avoided, particularly during the adjustment phase, unless it is specifically needed because of excessive changes in the bed. Some movable-bed material should be introduced at the head of the model, if there is any movement or scour just downstream of the entrance apron, during operation with each flow.

52. If the movement of bed material is too little or too great, the model discharge for that flow should be increased or decreased until movement appears to be satisfactory. Another and possibly a faster method is to lower or raise the stage at the control gage until movement appears to be reasonable. In the first method, the

water-surface elevation at the control gage would be maintained at the correct reading for that flow regardless of the change in model discharge and would require manipulation of the discharge and tailgate. With the latter method, only manipulation of the tailgate would be required and the stage being reproduced determined from the water-surface elevation at the control gage. The model discharge and the prototype discharge for the stage set on the model would be used to determine the discharge scale relation. A time scale is not used during this operation but gage readings should be taken and recorded after the flow, which appears to be satisfactory, has stabilized before going to the next flow.

53. The model discharge used in developing movement of bed material during the preliminary adjustment should then be used to determine the model-prototype discharge scale relation for the representative flows tested. These results should be plotted on the preliminary discharge relation curve and used to develop a modified curve. If there is a wide variation in one or more points that would not form a reasonable curve, the flow which appears to be out of line with the others should be rechecked and possibly additional flows above and below that point reproduced until a reasonable discharge relation curve can be established. A plot of the water-surface profiles obtained during the preliminary adjustment might also indicate which of the flows should be rechecked. These preliminary runs should be conducted by experienced technicians and each flow observed by an engineer experienced with this type of model. It would be helpful to plot on the spot the discharge scale relation established for each flow before changing to the next flow. If indicated by the plot, some additional adjustment in the discharge could be made and observed to determine if the adjustment indicated by the curve is satisfactory. If the curve is available on the model and plots are made by the operator as each flow is completed, adjustments can be made without excessive operation of the model with that flow and considerable time can be saved by extrapolating for the next flow.

Movement of Bed Material

54. In the preliminary adjustment, there is always a question as to when the movement of bed material for a particular flow is reasonable. In this adjustment there are two important points to remember. First, the amount of movement that should be obtained for each flow has to be based on the principles of sediment movement in alluvial streams and the experience and judgment of the engineer or technician conducting the study, guided by the following general rules:

- a. Movement in the model should occur during all flows that movement can be expected in the prototype.
- b. During low flows, movement of bed material will be mostly in crossings and shallow reaches with little or no movement in the deep channel such as bends and narrow reaches. Most of the material eroded from crossings and shallow reaches would be deposited in the deep channel downstream.
- c. Movement of sediment during high flows should be fairly general throughout the model reach but greater in bends and narrow deep channels than in the wide shallow channels or crossings. Some shoaling should be expected in the crossings and wide shallow reaches during these flows.
- d. The time with respect to the hydrograph when the prototype survey to which the bed of the model was molded should provide some indication of the type of movement that can be expected. A survey made at the end of a high-water period should indicate deeper channels in bends with shallower crossings; accordingly when starting with low flows, more movement should be expected over the crossing during low flows than if the survey were made at the end of a long low-water period. A survey made at the end of the low-water period would indicate that the bendway channel would tend to get deeper during high flows and the crossings, shallower.

55. The second important point to remember is that adjustment of the model is not an attempt to reproduce prototype slopes. With a varying discharge scale ratio and roughness of the bed which cannot be controlled, it is not possible to reproduce slopes with all flows. Water-surface elevations should be maintained as required at the control gage which should be near the center of the problem area during the adjustment phase. With this procedure the water depth is always correct

at that point and if the model slopes are higher or lower than those indicated by the prototype slope profile, the differences in water-surface elevations will increase progressively toward the upper and lower ends of the model. The maximum difference will always be away from the problem area and be less than and in most cases about half what it would be if the water level were controlled at one end of the model.

56. Although water-surface slopes are not being reproduced or adjusted, gage readings should be taken and plotted with and without supplementary slope adjustments. These slopes should be studied to determine what is happening in the model and whether or not the supplementary slope provided is reasonable for the discharge scales used. When the actual slope between two or more gages is too high or stages at the control gage cannot be lowered sufficiently, it could be an indication that the supplementary slope through that reach is insufficient. If the natural model slope is relatively small and the slope with supplementary slope adjustment is negative, it could be, but not necessarily, an indication that the supplementary slope applied was too much. Any adjustment in supplementary slope introduced in the curb rails will have some effect on the elevation of the molded bed and test results and should be made only after a careful study of the behavior of the model as well as the model slopes. During low water, slopes in the deep channel are naturally flat (could be negative with supplementary slope adjustment) and steep over crossings. The higher flows would tend to provide a more uniform slope through the reach and should be given some weight in evaluating the need for adjustments in the supplementary slope. It should also be considered that because of the distortion of the linear scales, the supplementary slope required in a deep narrow section is different from that required in a wide shallow section, particularly for the lower flows.

Rate of Introducing Bed Material

57. A sediment-discharge curve should be developed based on curves previously used with similar models and modified for any differences in

model scales or size of channel or both. If prototype curves showing rate of sediment movement with discharge are available, they can also be used as a guide. When using prototype information, only the grain sizes generally found in the bed should be considered. Whether the prototype sediment data were based on measurements, computations, or both, the location for which the data were developed should be determined. Sediment computations are usually based on average slope and depth, without consideration of channel alignment, and could be in error by more than 100 percent, particularly in the relative movement of sediment between high and low flows. The sediment-discharge curve should be plotted on log-log paper with river discharges or stages being reproduced versus model bed load in cubic feet per model day (Figures 4 and 5). From this curve the amount of bed material to be introduced is computed for each stage in the model hydrograph and the number of days duration.

58. The amount of material computed should be introduced on the apron during the operation of the hydrograph, and the behavior of the material introduced should be observed. If the amount of material introduced is insufficient as indicated by the scouring action just off the end of the apron, additional material should be added and the amount recorded. If the material introduced does not move, introduction of the material should be continued unless the accumulation appears to be excessive. In any case, the nature of the movement of material on the apron should be noted and some adjustment in the amount of material added might be indicated which could be made during the succeeding flows. It should be remembered that during certain flows deposition will occur and the material deposited will move with other flows. The ultimate decision as to whether the amount of material introduced is too much or too little will have to be based on whether the model channel with respect to the prototype is aggrading or degrading.

59. If the material introduced in a narrow deep channel or in a bendway channel does not move during most flows it could be an indication that the supplementary slope is not properly distributed in accordance with the channel cross section. Material should always be

introduced laterally on that portion of the apron where movement is indicated or where movement should be expected for that flow. If the location of movement is not what would be expected for the flows reproduced, some adjustment in the distribution of flow entering the model might be indicated. Evaluation of sediment movement to be expected should be based on channel alignment with respect to the reach upstream, channel cross section at the apron, and river sedimentation processes. During low flows there will be a tendency for deposition in a narrow deep channel, particularly on the concave side of a bend. The material deposited during low flows will begin to be eroded as the discharge increases. The erosion will start at the upstream end of the bend and move toward the downstream as the discharge and stage increase. In a wide shallow channel or crossing, erosion of the channel bed usually occurs during the lower flows with the material eroded moving into the bendway channel downstream. During the higher flows, some shoaling will occur in the wide shallow reach because of scouring in the bendway channel and the difference in the rate of movement between the two reaches.

Time Scale

60. A time scale will be required to reproduce the sequences and durations of the various stages and discharges indicated by the hydrograph. The time scale should be such that it indicates a relation between the time required for developments in the model and that in the prototype. In order to develop a reasonable time relation, it would be necessary to know the rate of development in the prototype as indicated by successive surveys. Sufficient data are seldom if ever available and some of the progressive changes affecting developments such as dike construction, dredging, and bank caving would be difficult to reproduce in detail on a timely basis. Satisfactory results have been obtained using a time scale of 6 to 10 minutes for each prototype day with sand-bed models and 5 to 8 minutes per day with coal-bed models. Generally, the rate of development in the model is affected to a considerable extent by the discharge scale. In some cases it might be advisable to modify the

time scale rather than the discharge scale if the trends are correctly reproduced but the rate or amount of development is incorrect.

Adjustments with Hydrograph

61. Operation of the model by reproducing the verification hydrograph should be undertaken only after the initial adjustment with the representative flows appears to be satisfactory. Unless the bed of the model has been disturbed excessively during the preliminary adjustment, the model need not be remolded for the first run since it is very unlikely that a satisfactory verification will be developed without additional adjustments. Reproduction of the hydrograph should be based on the discharge scale relation developed during the preliminary adjustment and a time scale used on similar models that produced satisfactory results. It is important that close observation of developments in the model be maintained during this operation and significant results be recorded.

62. Observations should be concerned with conditions near the entrance and exit and with changes in the bed produced by the various flows reproduced. During the first reproduction of the hydrograph, some additional adjustments could be made in the discharge scale based on observation of each flow. Any adjustment made on one flow should be plotted on the discharge relation curve and used to adjust the remaining portion of the curve for use with other flows. Regardless of any adjustment in the discharge relation, the stage should be maintained at the control gage near the center of the model or problem reach. Flows that produce no movement of the bed material should either be adjusted by increasing the discharge scale relation or discontinued after it has stabilized.

63. Flows that produce little or no movement of the bed material would not contribute to the development of the channel and should not be reproduced in the interest of time and cost until such time that an improvement plan or modification might indicate that these flows would have some effect. Before any flows are eliminated from the model

hydrograph, a careful study should be made of the prototype water-surface slopes, velocities, and any other information that might provide a clue as to the sediment movement in the river. Normally with open river conditions all flows would contribute to channel development. Velocities during flows affected by backwater such as flow from a tributary stream downstream of the model reach, by locks and dams or reservoirs, tides, etc., could be reduced sufficiently to reduce or prevent any movement of sediment affecting channel development, particularly during the lower flows.

Adjustment of Bed Movement

64. Insufficient movement of bed material would indicate the need for an increase in the discharge scale relation and possibly some adjustment in the supplementary slope. Changes in the discharge scale might be through the entire range of flows or just the low, medium, or high flows depending on the results of observation of the model during operation. Notes of the model operator and periodic observation by the engineer in charge would be of assistance in determining the changes needed. The best method of determining when and during what flows critical changes are occurring is to obtain a few soundings at the beginning and ending of a high-water period and during a medium flow. Changes in supplementary slopes should be based on a study of model water-surface slopes in addition to the rate of bed movement and whether the channel bed is aggrading or degrading. Generally, increasing the supplementary slope upstream of the control gage would tend to increase movement in that reach while an increase in the supplementary slope downstream of the gage would tend to reduce sediment movement in that reach. Special consideration should be given to the discharge scale ratio for flows that are affected by backwater from another stream, tides, powerhouse releases, or dam operation. The discharge scale ratios for some of these flows would have to be modified based on changes in slope or velocity for the same total discharge.

65. The effects of any adjustments should be evaluated and

recorded. If the adjustment is in the right direction, it can be modified as to the amount required. If the adjustment produced an undesirable effect, it should be noted in order that it not be repeated in future tests. Before determining the adjustments that should be made in subsequent tests, the effects of previous adjustments should be considered based on the recorded evaluations rather than on memory. Evaluating the effects of any adjustments and the processes involved is an excellent method for developing a knowledge of river sedimentation processes and the basic principles of river hydraulics.

Channel Alignment

66. An important development in the prototype that could be difficult to reproduce in the model is that of channel alignment, particularly in wide shallow reaches. Channel alignment is affected by river stages and discharges, alignment of banks, composition of the bed and banks, and flow distribution within the channel cross section. Flow distribution within movable-bed models is affected to some extent by the distortion of the velocity scale ratio which is higher than theoretical based on the linear scales and to changes in the width-depth ratio of the channel because of the differences in the linear scales. Distribution of flow and development of channel alignment can also be affected by the alignment of the bank or banks just upstream, the location of a gravel bar or a material resistant to erosion, remnants of old revetments or dikes, improper distribution of sediment introduced in the model, and method of reproducing active bank caving.

67. During operation of the model for the adjustment with the verification hydrograph, observations should be made keeping in mind any differences noted in channel alignment between model and prototype, and flow or flows during which the differences develop. Some flows will tend to modify the alignment of the channel in one direction while other flows will tend to change the alignment in the opposite direction. The difference in channel alignment between the model and the prototype should be evaluated and noted, including any difference in channel

depths and bar location and elevation. Local differences of a few feet (prototype) should generally be ignored except when project depths over a crossing could be affected. Most of the differences in channel alignment will usually start in a crossing just downstream of a bend.

68. In a distorted model, crossings will tend to be somewhat farther downstream than in the prototype which could be attributed to: the higher velocities in the model than the theoretical based on model verification scale ratio; effect of the higher flows being greater than the proportional effect of the lower flows; insufficient sediment being moved toward the bar side of the crossing; and improper reproduction of the model bank line due to inadequate prototype data or improper interpretation of data between templates or ranges. The first step that should be taken when there is a significant difference in the channel alignment is to check the alignment of the banks upstream for any features that could affect the direction of flow and movement of sediment in the reach. A good aerial photograph can often show irregularities in the bank line that might not be sufficiently detailed on the map. The possibility of errors in the prototype surveys and the existence of erosion-resistant material should also be considered.

Successive Adjustment Tests

69. The number of adjustment tests required before a satisfactory verification is developed will depend on many factors such as the characteristics of the prototype reach, nature of the problem, amount and type of field data available, developments within the reach, model scales, experience and judgment of the engineer in charge, control of sedimentation processes, dedication of technicians conducting the study, and refinement to which the adjustment is carried. Normally, a satisfactory adjustment would require 3 to 6 months but in special cases would require more than 1 year. Estimates of the verification period should be based on a period of 6 to 9 months for models of most reaches and 9 to 12 months for models of reaches complicated by unusual developments caused by tributaries, distributaries, divided flow, or flows affected by tides, reservoirs, etc.

70. Adjustments for each successive run should be based on the differences in the developments within the model and those indicated by prototype surveys used for the verification, observations made during the preceding tests, and the probable causes of the differences based on the evaluation of the prototype and model data. Results of the evaluation might indicate the need for adjustment of one or more of the following:

- a. Discharge scale
- b. Time scale
- c. Rate and method of introducing bed material
- d. Supplementary slope
- e. Entrance and exit conditions
- f. Bank alignment and overbank roughness
- g. Areas where developments might be affected by erosion-resistant material
- h. Elevation and condition of regulating structures

71. Arbitrary adjustment of any of the factors listed without an adequate evaluation of developments during previous tests and the effects that can be expected from such adjustment would be a trial-and-error approach which could result in a considerable loss of time and effort. Also, any adjustment made should be of sufficient magnitude to provide a definite indication of its effects on the results.

72. It should be considered in the evaluation of results and application of adjustments that most of the developments within an alluvial stream occur in three dimensions and are dependent on the Franco principle of lateral differential in water level which is stated as follows: when conditions are such that a lateral differential in water level (or transverse slope) exists or is produced by changes, there will be a tendency for at least some of the total flow to move toward the lower elevation; the slower-moving sediment-laden bottom currents can make the change in direction easier than the faster-moving surface currents and account for the greater concentration of sediment moving toward the lower elevation. This principle is involved in the development of sandbars on the convex side of bends, performance of dikes,

development of cutoffs and divided channels, shoaling in lock approaches, etc. In such cases, either an increase or decrease in water level on one side affects the movement of sediment and channel development.

Final Verification

73. The adequacy of the adjustment is sometimes difficult to determine and has to be based on the problem or problems to be resolved and the accuracy required in the final results. In most cases involving channel development, the principal factors to be considered are channel alignment, controlling depths, and reproduction of the problem or problems to be resolved. If the problem or problems are not reproduced at least qualitatively, the effectiveness of the various proposed plans cannot be adequately evaluated. Reproduction of the instability of some prototype reaches, where frequent changes occur in location, alignment and depth of channel, and location and size of sandbars, could be difficult and sometimes impossible. Instability, particularly in wide shallow reaches, could be caused by the rate of rise and fall of river stages which cannot be reproduced accurately in most models or by the chance occurrence of sand waves, especially when there is a rapid drop in river stage. Conditions that are not reasonably consistent from one season to the next in the prototype stream need not necessarily be reproduced accurately in the model before an adjustment is accepted as adequate. When only one survey is available, it is difficult to determine the consistency of the development in an unstable reach and the determination would have to be made on an evaluation of channel configurations and the probable effects of various flow conditions. In most cases, it would suffice to adjust the model to reproduce general tendencies.

74. The final adjustment that is accepted as a satisfactory verification should be carefully evaluated as to the degree of similarity. The tendencies of the model to be different from the prototype insofar as channel alignment and depths should be noted and considered in the evaluation of the results of tests of improvement plans. The tendencies

of the model to be different from those of the prototype could be accumulative which would not necessarily be indicated by the reproduction of a hydrograph covering a period of about a year. The consistency of the model in reproducing certain tendencies would be indicated by the base test or by repeating the verification hydrograph without remolding the bed.

75. The successful verification indicates the degree of similarity that can be expected between the model and prototype and establishes the scale relations to be used in subsequent tests. In most studies the time scale is necessarily established arbitrarily based on experience and judgment, since sufficient prototype data depicting the rate of change of conditions in the field are seldom, if ever, available.

PART V: BASE TEST

Purpose

76. Before tests of improvement plans are undertaken, a base test consisting of several reproductions of a typical hydrograph should be conducted. The purposes of this test are to determine the general tendencies for developments within the reach with time as affected by the typical hydrograph, and any accumulative differences between model and prototype that could affect the interpretation of the results of tests of improvement plans. Results of the base tests would also provide a basis of comparison in determining the effects of various proposed plans. Without the base test, any accumulative changes or changes caused by differences in flow conditions and duration of tests might be wrongly attributed to the effects of the proposed plans.

Hydrograph

77. The hydrograph used for the base tests should be based on stage and discharge frequency curves, usually eliminating flows that have a low chance of occurrence. Generally, it is not practical to design channel development plans for extremely high or low flows unless these flows are the principal contributors to the problem or problems to be resolved. The hydrograph to be used for the base test and tests of improvement plans should be furnished by the sponsoring office but should be reviewed by the agency conducting the study as to its adequacy. In some cases, it might be advisable to test proposed plans with the typical hydrograph and again with extreme or unusual hydrographs. If the need for the additional tests can be anticipated, the extreme hydrographs should be reproduced as part of the base test. Since this hydrograph would be experienced infrequently, one reproduction conducted after the model has stabilized using the typical hydrograph should be adequate.

78. The base test should be conducted using the relations

developed during the adjustment and verification. The need for the development of a discharge relation curve and a sediment-discharge curve during model verification becomes obvious since it is often necessary to obtain model operating data for flows that might not have been included in the verification hydrograph. Water-surface elevations for each stage should be maintained at the control gage used for model verification (near center of model). The results of the base test will also establish the relation between discharge and water-surface elevation at a gage near the end of the model that would be used for control during tests of improvement plans.

Evaluation of Results

79. Results of the base test should be evaluated on the basis of general tendencies compared with the tendencies indicated by the prototype surveys, and differences between the model results obtained in the verification test and river conditions indicated by the prototype survey at the end of the verification period. The evaluation should be based on tendencies for the channel in the model to be stable or unstable, controlling depths and channel alignment from reach to reach, water-surface elevations and slopes for representative flows, and tendency for the channel to aggrade or degrade. Results of this evaluation should be summarized and considered when evaluating the results of tests of improvement plans.

PART VI: TESTS OF IMPROVEMENT PLANS

General Procedure

80. Development and testing of improvement plans are usually the principal purposes of the model study. Before these tests are undertaken, the adequacy of the verification and base tests should be considered in the light of the type or types of plans being studied or might be considered before a satisfactory solution is developed. The test of improvement plans could be started with the bed of the model remolded or with the model bed as obtained at the end of the base test. If there is a considerable difference in the bed of the model caused by operation with several reproductions of the hydrograph, it is better to remold the model bed, particularly if the changes obtained during the base test would not be permitted to develop in the field.

81. Plans in river development usually are concerned with improvement of width, depth and alignment, and stabilization of the channel for navigation and/or for flood control and usually involve various types of construction such as contracting and training structures, dredging, cut-offs, and in some cases locks and dams. During installation of the plan, the adverse effects of the distorted scales and compensations that should be made to reduce the effects (as mentioned in paragraph 25) should be considered. Operation of the model for tests of improvement plans should be based on the reproduction of the typical hydrograph used for the base test. During the operation, water-surface elevation for each flow should be controlled at the lower end of the model based on data obtained during the base test for each flow to permit the model to react to any changes in water-surface elevations that might be caused by installation of the improvement plan.

Development of Plans

82. In development of improvement plans the type or types of problems to be resolved, the conditions contributing to the problem, flows

during which the problem develops, and the changes needed to eliminate or reduce the conditions adversely affecting the problem should be considered. The design of training and regulating structures should consider the effects of the proposed structures on currents and the movement of sediment and the effects of the resulting currents on navigation. This should be considered in three dimensions based on the principle of lateral differential in water level mentioned in paragraph 72 which is involved in many of the developments in alluvial streams and should be a major factor in the design of structures and in the development of general plans. It should be considered that the lateral differential in water level is created either by a rise in the water level on one side or by a reduction in the water level caused by centrifugal force, dikes, channel enlargement, flow diversion, or tributary flow that results in a change in direction of some of the flow. Structures concerned with sediment movement, therefore, should be designed to develop or reduce this lateral differential in water level, depending on the mission to be accomplished.

Application of Principle

83. A system of spur dikes for the purpose of realigning the channel or to increase depths by contraction of the channel should be designed to develop the lateral differential in water level that would cause the movement of sediment away from the channel into and within the dike system. This effect is produced by the step-down dike system in which the first dike on the upstream end has the highest crest elevation with each succeeding dike having a crest some 2 to 5 ft lower than the dike just upstream.

84. The step-down principle is ideal for dikes designed to increase depths over crossing and would provide better results at a lower cost since the longer dikes toward the downstream would be at progressively lower elevations. In a system containing many dikes, the step-down principle cannot be continued indefinitely since the elevations of the dikes some distance downstream would be too low to have any

effect on channel development. In such cases, it might be better to have the step-down effect on the first three or four dikes and have the remainder of the dikes maintained at the same elevation as the lowest dike in the step-down group. With the step-down system, the lower dikes can be longer (even extend beyond the channel control limit line) than if the dikes were at the same elevation as the higher dike without contracting the channel more than the shorter but higher dikes.

85. In some cases a reduction of the lateral differential in water level is needed to eliminate shoaling or to reduce the sediment-water ratio such as with a diversion channel or powerhouse intake. The prevention of shoaling in lock approaches, harbor entrances, or in some cases entrances to side channels usually cannot be accomplished by contraction structures. The solution of these problems would require the reduction in the movement of bottom currents into the problem area. This can often be accomplished by low structures that would permit surface flow into the area, thus reducing the lateral differential in water level near the ends of the structures and preventing the heavy sediment-laden bottom currents from moving around the ends. The wing dike developed for use in the lower lock approaches has been successful in reducing the amount of shoaling and frequency of dredging required in the approaches.

86. Spur dikes with L-sections having lower crests than the dikes to which they are attached will tend to prevent sediment from moving in behind the dikes when the L-sections are overtopped without substantial overtopping of the spur dikes. The reason for this is that the surface flow over the top of the L-section tends to reduce the lateral differential in water level and the amount of bottom currents that would normally move around the end of the main dike or L-section. The surface flow over the top of the L-section could cause some scouring along the landward side of the L-section. L-sections are not as effective in preventing deposition landward during flows that substantially overtop the main dike but produce some benefits when little or no sediment is moving over the top of the main dike.

Testing Program

87. Maintenance of suitable records of operations, changes in plans, and developments should be an important part of the testing program. For each test an accurate description of the plan being tested should be made at the time of installation or soon after for record and for the final report. Considerable time can be lost during the preparation of the final report when research is required to determine exactly what existed in the model before the test of a particular plan was started, changes made as a part of the improvement plan, and reasons for the changes. Also, it is important that some record be made of developments during the test with a summary of the results of the test. The results are generally evaluated and discussed to some degree with or without the sponsors as to the effects of the plan, the processes involved, and the need for modification. Making a notation of the results of the evaluation and discussions can reduce the time and work involved in the preparation of the final report. It would be ideal if each test could be written in final form within a few days after completion of each test. This is not always practical because of the press of other work and interruptions, but at least a few notes based on the initial evaluation can be invaluable and could eliminate some of the difficulties experienced by many engineers in preparing final reports.

Interpretation of Results

88. Evaluation and interpretation of the results of movable-bed studies should consider the results of the verification and base tests. These results will indicate the degree of similarity between model and prototype and the developments that can be attributed to the normal tendencies within the reach with the typical hydrograph selected for the study. This evaluation should be made soon after the two tests are completed and the results made available for the evaluation of the tests of improvement plans.

89. Interpretation of results should consider the effects of

distortion not only as affected by the linear scales but also as affected by the varying discharge scale relation. In determining the effect of structures on water-surface elevations, the measurements taken in the model should be adjusted based on the difference between the velocity scale used for the flow during which the measurements were taken and the theoretical velocity scale based on the model vertical scale. For instance, if a change in stage of, say, 2.0 ft (prototype) is measured in the model as a result of the installation of a given plan during a flow having a velocity scale ratio of 1:8 instead of the theoretical scale ratio of 1:10, the difference should be adjusted by multiplying the amount of change by ratio of the theoretical velocity scale ratio squared (1/100) divided by the actual velocity scale ratio squared (1/64). In this case the adjusted change would be 1.28 instead of 2.0 ft as measured in the model. The reason for this is obvious since the change in stage is based on changes in $V^2/2g$ and $2g$ is constant. When the actual velocity scale is larger than the theoretical velocity scale based on the square root of the vertical scale, the corrected change in stage will always be less than that measured in the model and should be so reported as the effect of the plan, if it is a significant part of the study.

90. The changes in the channel bed produced by a given plan should be based on those obtained in the base test and considered with the results of the model verification. For instance, if during the verification test the model was 3 ft too deep in reproducing depths over a crossing and the plan increased depths by 4 ft, the actual elevation in the model will still tend to be about 3 ft deeper than should be expected in the prototype under the same conditions. The reverse would be the case where the model was shallower than the prototype during the verification test. The effectiveness of a given plan, therefore, should be based more on the changes produced by installation of the plan than on the actual measurements made in the model particularly where depths are concerned. A plan that developed depths in a reach greater than those obtained in the base test should cause an increase in depths in the prototype under the same conditions. If one model plan is more

effective in producing the desired results than another plan, it will also be more effective in the prototype.

91. It should also be considered that channel development is dependent to a considerable extent on flow conditions and composition of the bed. Conditions obtained after a prolonged high-water or low-water period can be considerably different from those obtained with what might be considered as a typical flow period. Also, some differences can be expected when the prototype survey is made at a time with respect to a hydrograph which is different from the time of the model survey. Some significant differences in model and prototype developments have occurred because of the existence of bedrock close to the bed that were not known at the time of the model study.

92. Differences can also be expected where there are gravel bars, rock outcrop, hard clay, or remnants of old revetment or structures that are not reported or sufficiently delineated to permit accurate reproduction or simulation in the model. Without such information the model results have to assume that the prototype channel bed is composed mostly of the type of sand generally found in that particular reach of the river.

PART VII: SUMMARY

93. Many of the same general principles are involved in the development of rivers whether large or small. River models are small rivers patterned after a larger river and designed and adjusted to reproduce the essential characteristics of that river. With models, developments can be observed and measured and various plans can be installed and tested under the exact same conditions within a relatively short time at comparatively little cost. Experimenting with the prototype river can be expensive and the results cannot be adequately evaluated because of the difficulty in obtaining the data needed, variations in flow conditions before and after construction, and differences in channel conditions from reach to reach. Because of the complex nature of alluvial streams, the optimum solution to many sedimentation problems and the answers to many questions regarding the performance and effectiveness of various types and arrangements of structures will have to depend mostly on the results of river model studies correlated with experience in the field.

94. The processes within a movable-bed model are as complex as those within an alluvial stream and developments depend on many interrelated factors. The design, adjustment, and operation of these models should depend on the characteristics of the stream reproduced, nature of the problem or problems to be investigated, and the type of results needed. The successful adjustment of these models and the results obtained will depend to a considerable extent on the knowledge of sedimentation processes, prototype data available, experience with laboratory procedures, and dedication of the engineers and technicians conducting the studies. An important factor in these investigations is the interpretation of model results with respect to their application to conditions in the field. This interpretation should be made by the laboratory engineer familiar with prototype developments, model limitations, and conditions imposed on the model.

95. River models are used to develop comprehensive and detailed plans for the improvement or development of specific reaches, for the

development of general principles affecting processes within alluvial streams, and for the design of training and stabilization structures. In the study of problems in specific reaches, models are used to determine: conditions that can be expected with a proposed design, relative effectiveness of alternate plans, modifications that might be required to eliminate any undesirable conditions or to reduce construction and maintenance cost, and the best method and sequence of construction. For general studies, models are used to study typical problems encountered in alluvial streams for the purpose of developing general principles involved in the development of these problems which can be used by the river engineer as a basis for the design of general plans and structures. Models are also used to demonstrate for interested parties the processes involved and conditions resulting from a proposed plan in order that they can satisfy themselves as to its acceptability and to receive their comments and suggestions.

APPENDIX A: CHARACTERISTICS OF MODEL BED MATERIAL

1. The selection of a bed material suitable for use in movable-bed models has been the subject of considerable study and research. Various materials have been tried by different laboratories but only a few have continued to be used. Some of the materials that are in use or have been tried are listed below with some of the characteristics that could affect their selection as model bed material.

Sand

2. Sand is readily available and has a rather uniform specific gravity of about 2.65. It is found in the bed of most alluvial streams regardless of the size of the stream. Smaller streams, in order to compensate for the smaller depths, need steeper slopes to provide the energy required to move the proportional amount of sand as the larger rivers. In order to reduce the forces required in model streams, the grain size of the sand used should be as small as practicable. The size used at WES has a mean grain diameter of about 0.20 mm. Sand is reasonably stable and is not affected appreciably by weather. Heavy rains can cause some erosion of the sand bed when exposed above water, but in most cases the damage is either insignificant or can be repaired without any serious effect on the test in progress. Sand must be washed to remove clay and fine silt before it can be used in the model. Clay and silt can cause a crust to form on the surface of the model bed that will affect movement of the bed material and channel development. In outdoor models, the movement of bed material can also be affected by the growth of algae. A disadvantage of using sand in addition to the greater forces required to be moved than a lighter material is the formation of ripples on the model bed. These ripples have a significant effect on flow, particularly where depths are small. In prototype rivers the sizes of ripples are so small in comparison with the size of the river that they can be ignored as a factor in the development of the channel bed. Ripples not only affect channel roughness in the

model but produce irregularities in channel depths. With small vertical scales, the irregularities can be significant and should be balanced to eliminate the high and low points when preparing a map of the bed.

Coal

3. Coal is the most common type of bed material used at WES. This is a special coal free of impurities having a specific gravity of 1.3 and as such is about 5.5 times lighter than sand when submerged in water. Coal, when properly sized, can be moved without ripples. Coal beds having large quantities of small grain sizes will tend to form ripples, particularly when water temperature is lowered to less than about 60°F. Coal has to be screened, or crushed and screened, depending on the sizes purchased and washed thoroughly to remove dust. It is generally not practical to use coal in models constructed outdoors because of the effects of the weather.

Plastics

4. Plastics can be obtained in a variety of sizes, shapes, colors, and specific gravities. It would appear that this would be an ideal material for movable-bed models. However, use of plastics having a specific gravity substantially less than that of coal (1.3) has resulted in excessive floating of the material due to surface tension effects. Use of a wetting agent has permitted its use in tracing the movement of bottom currents and to indicate areas of scour and deposition. In models with changes in discharge and river stages, the material will tend to dry out during low flows and float as the stage heights increase. The same effect is obtained when the model is drained and then refilled for additional testing. Plastics have been somewhat expensive even when obtained as a by-product, and firms have been reluctant to supply small quantities in the size and shape required for the study.

Pumice and Haydite

5. Pumice and haydite have not been used as bed material in river movable-bed models at WES. These materials vary as to their submerged

weight and movability because of various amounts of air trapped in the material. Pumice of relatively large grain sizes has been used in some European laboratories. This material, usually mixed with coal to provide material moving in suspension, does not contribute to the model channel development but is included to indicate the movement of material that goes into suspension and areas where such material might be deposited. Such material might be useful in reproducing bank caving or dredging operations where a sizable portion of the material being caved or dredged is clay or fine silt which moves mostly in suspension and does not remain in the channel.

Walnut Shells

6. Use of ground walnut shells has been observed in only one laboratory of the many visited in this country and in Europe. This material has a specific gravity of 1.3; has a tendency to decompose producing gas, discoloration of the water, and an objectionable odor; and has a tendency to cake. Gas bubbles have been observed to float out the caked material in large chunks. Observations indicate that when moving in water the material becomes rather fluffy, forming in large ripples. The bed of the model is so fluffy that it has to be surveyed underwater with an echo sounder and so irregular that several cross sections have to be averaged out to indicate the effect of the operation. Tests observed using this material were conducted with a constant discharge throughout the test period and in a continuous circulating system.

Bakelite

7. Ground Bakelite has been used in movable-bed river models being conducted outdoors at one of the European laboratories. The bed material observed appeared to be rather large (about 1/4 in.) and cubical in shape. The model using this material appeared to be highly distorted, indicating the specific gravity of the bed material to be

higher than that of coal but probably less than that of sand. Because of the large grain size, models observed using Bakelite did not ripple but moved in rather large waves or dunes.

APPENDIX B: TOTAL MODEL SLOPE

1. Design of movable-bed models requires the determination of the model slope that would assure movement of the selected bed material in simulation of bed movement in the prototype. This slope is provided in most cases by distortion of linear scales with or without supplementary slope. The total slope, therefore, is the prototype slope multiplied by the degree of distortion plus supplementary slope, if any. The total slope needed can best be determined from experience with similar models.

2. The slopes used with some of the models at WES are listed in Tables B1 and B2. These slopes vary considerably but the differences between models of the same river are not as great as the differences between models of different rivers. Some of the differences can be attributed to the use of average river slopes which might be considerably different from the actual slope in the reach reproduced. The effect of using a supplementary slope that is not exactly correct will not seriously affect results since adjustments are made for any discrepancies that might be indicated. With the variable discharge scale relation, slopes will never be correct for all flows. The model will tend to adjust its slope based on the discharge scale imposed and rate of bed feed, and the results might indicate the need for modification of the discharge scale to compensate for the incorrect supplementary slope. In models of short reaches, the effect of incorrect supplementary slope is small. In models of long reaches, the bed adjusting to the correct slope for the discharge and bed material imposed could affect the depths measured unless the curb rails are adjusted to compensate for the change, particularly with smaller vertical scales. For instance, a 400-ft-long model with a difference between the supplementary slope incorporated in the model rails and that to which the model adjusts itself is on the order of 0.0002, the error in the bed elevation measured could be as much as 0.08 ft or 8 ft with a vertical scale of 1:100. With the correct water-surface elevation maintained at the center of the model in this case, the difference in the bed elevation measured

at the center would be correct and error or differences would increase progressively toward each end of the model to a maximum of about 4 ft.

Table B1
Supplementary Slope, Sand-Bed Models

Project	Length miles	Model Scales	River ft/mile	Slope		Time Scale min/day
				Natural Model	Supplementary Total	
Channel Development, Ark. R.	11.1	1:150-1:36	0.75	0.000593	0.00005	0.000643
Island 63, Miss. R.		1:400-1:60	0.45*	0.000568	0.000250	0.000818
Caruthersville, Miss. R.		1:540-1:60	0.40*	0.000681	0.000365	0.001086
Cracraft-Sarah Island, Miss. R.		1:480-1:60	0.38	0.000575	0.000369	0.000945

* River slopes estimated.

Table B2
Supplementary Slope, Coal-Bed Models

Project	Length miles	Model Scales	Slope			Time Scale min/day
			River ft/mile	Natural Model	Supplementary Total	
L&D 13, Ark. R.	12.8	1:120-1:80	0.75	0.00021	0.00007	0.00028
L&D 4 Div, Ark. R.	3.8	1:120-1:80	0.75	0.00021	0.00007	0.00028
L&D 8, Ark. R.	11.0	1:120-1:80	0.75	0.00021	0.00011	0.00032
Dardanelle, Ark. R.	*	1:120-1:80	0.58*	0.000165	0.00025	0.000415
Confluence w/Verdigris R., Ark. R.	5.7	1:120-1:80			0.00021	0.00021
L&D 13, Ark. R.	11.3	1:120-1:80	1.20	0.000341	0.00015	0.000491
Typical Reach, Red R.		1:150-1:100	0.62	0.000176	0.00041	0.000586
L&D 1, Red R.		1:120-1:80	0.62	0.000176	0.00042	0.000596
Lower Reach, Red R.	4.5	1:120-1:80	0.62*	0.000176	0.00063 0.00045	0.000806 0.000626
St. Louis Harbor, Miss. R.	21.1	1:250-1:100	0.44*	0.000208	0.000132	0.000340
Suck Bend, Chattahoochee R.		1:72-1:72	*	*	none	*

* Slopes varied with discharge because of reservoir, backwater, tributary flow, or changes in channel characteristics.

APPENDIX C: CHECKLIST FOR MODEL DESIGN AND OPERATION

1. Preliminary Evaluation and Cost Estimate

- a. Establish and keep in mind purpose of investigation.
- b. Determine nature of problem, processes involved, and probable solutions.
- c. Review and list prototype data available.
- d. Determine flow and sediment characteristics of the stream and maximum and minimum stage and discharge.
- e. Determine reach and overbank area that should be reproduced for the study.
- f. Determine model scales suitable for the study.
- g. Determine additional data needed and information that would be helpful.
- h. Determine sites available for the model and additional facilities needed at each site.
- i. Prepare cost and time estimates for model design and construction, including contingencies for increases in cost, and additional facilities if selected site is not available at time study is authorized.
- j. Prepare estimate of cost of operation per month, including molding of model bed, photography, and drafting. Estimate total cost of study based on assumed operation period and preparation of final report.

2. Design of Model

- a. Have complete list of data available including coverage, type of information, and dates.
- b. Review purpose of the study, type and accuracy of results required, and probable solutions to determine adequacy of model scales and areas to be reproduced.
- c. Select data to be used for model layout and features to be reproduced.
- d. Establish suitable horizontal controls for use in template layout and layout of channel center line, model limits, and gage locations.
- e. Determine areas to be reproduced in movable material and those to be fixed. Provide flexibility that might be required for adjustment and installation of improvement plans.
- f. Plot profile of channel thalweg to determine elevation of trough for bed material. Consider requirements for draining and flooding of model.

- g. Determine prototype water-surface slopes and supplementary slope based on total model slope required (Appendix B).
- h. Prepare template layout based on channel configuration and bank alignment.
- i. Establish base elevations for overbank templates and elevation of checkpoints that would provide for supplementary slope. Elevation of checkpoints with respect to model grade should be the same for templates in same general area.
- j. Determine water supply and measuring equipment needed for range of flows to be reproduced. Provide flexibility for adjustments.
- k. Select locations for model gages based on location of any prototype gages, breaks in water-surface slope indicated, or breaks that can be expected based on channel configurations and proposed improvement plans.
- l. Plot templates providing for essential features. Channel ends of overbank templates should provide smooth alignment of the fixed banks where there are no abrupt changes in bank line.
- m. Prepare construction drawing showing model layout at site selected including water supply system; gages; location of a suitable permanent bench mark; base elevation of model with respect to the average ground elevation, adjacent model, or other existing structure; and location, type, and grade of curb rails.

3. Inspection of Model Construction

- a. Be familiar with significant prototype and model data available and basis of model design.
- b. Have map available and use for sketching. Maps should have list of special features that should be incorporated during construction and particularly those that require special attention.
- c. Maintain diary indicating progress, personnel responsible, special data or instructions, and changes in plans.
- d. Check layout of templates for any that might appear to be improperly located or out of line. Check base elevations of model with surrounding area and need for drainage.
- e. Check carefully the alignment of the fixed bank with regard to scallops, protrusions, and changes in alignment between templates. Compare with any aerial photographs that might be available.
- f. Check alignment of contours between templates along overbank including depressions or ridges extending to or from top bank.
- g. Check size of water supply lines and venturi meters at time of installation. Record information, date, and name of checker.
- h. Check bed material for size and cleanliness before being placed in model.

4. Preparation of Data (During Design and Construction)

- a. Prepare and maintain up-to-date list of prototype data including type, coverage, dates, and notations with regard to information used or that might be significant in the design, adjustment, and operation of model.
- b. Plot slope profiles for representative flows based on prototype records for use in model design and operation.
- c. Prepare master sheet for use in recording model data and which can be used for the final report.
- d. Prepare map of channel bed based on prototype surveys to be used for molding model bed and for comparison with model results. Use master sheet.
- e. Plot stage hydrograph for verification period and block off into a series of constant stages suitable for model reproduction.
- f. Develop stage-discharge relation for hydrograph developed in e. above.
- g. Develop preliminary discharge scale relation curve based on model scales and experience with similar models.
- h. Prepare preliminary sediment-discharge relation based on model scales and experience with similar models.
- i. Develop model operation data for representative flows based on relations developed above.

5. Molding Movable Bed

- a. Close supervision should be provided by an experienced engineer or technician.
- b. Contoured map of the bed should be readily available and used to check molding between templates. Note particularly the alignment and elevation of channel bed and sandbars from one template to the next.
- c. Check placement of fixed sections of the bed as to elevation, extent, and transition between fixed and movable bed.
- d. Check location and elevation of training structures and molding between structures.
- e. Observe model bed during initial flooding to determine any low or high areas between templates as indicated by water level.

6. Preliminary Adjustment

- a. Check gage elevations (zeros) based on bench mark elevation and spot-check elevation of gages and rails with a level pool.
- b. Bleed manometers and venturis.
- c. Have water in model at least as high as the elevation of the stage to be set before introducing flow into model. Sand-bed

models should be started with highest flow to permit formation of ripples.

- d. Increase discharge to the proper setting before lowering tailgate to obtain correct stage. Tailgate should be lowered gradually and action in model observed.
- e. If movement of bed material appears satisfactory before the water level for that stage is reached, either maintain that level and read gages, or decrease discharge to provide correct stage and same movement. Purpose of operation is to obtain satisfactory movement of bed material for representative stages and discharges; stages need not be exactly as selected to develop a discharge curve. When satisfactory movement of the bed material is obtained with a given discharge, considerable time can be saved by using that discharge and the stage indicated by the control gage to develop the discharge scale relation curve.
- f. If movement of bed material is inadequate, either lower the stage until movement for that discharge is satisfactory or increase discharge and readjust stages.
- g. Raise tailgate before increasing discharge when going from lower to higher stage; decrease discharge before lowering the tailgate when going from higher to lower stage.
- h. Develop discharge scale relation curve based on actual stages reproduced. Make such adjustments in flows that appear out of line or reproduce additional flows above or below those flows until a reasonable curve has been developed.

7. Model Verification

- a. Remold model bed if disturbed excessively during preliminary adjustment.
- b. Operate model by reproducing verification hydrograph; maintain stage at control gage near center of model or problem reach.
- c. Observe movement of bed material and record any unusual occurrences. Make adjustments obviously needed during operation with first hydrograph.
- d. Survey model bed after each reproduction of the hydrograph and evaluate results based on comparison with prototype survey and a study of model water-surface slopes. Record results of the evaluation including list of differences and probable cause. Determine additional adjustments required after reviewing the effects of previous adjustments.
- e. Make adjustments in model and operating procedure indicated above and repeat test. Magnitude of adjustment should be such that its effect on developments will be indicated. As a general rule, avoid making more than one significant adjustment during the same run, since it would be difficult to determine the effects of each adjustment.

- f. Remold model bed before starting next test if warranted by changes during the previous run. Record adjustments made to the model and model operating procedure and purpose of the adjustment.
- g. Operate model and observe developments, particularly where model was different from prototype. Obtain spot-check of bed elevation in critical areas during reproduction of the hydrograph to determine which flows adversely affect developments.
- h. Survey model bed and evaluate results based on comparison with prototype, with previous model results, and observations made during operation.
- i. Maintain a readily available record of the evaluation of each run, including results, adjustments made, and effects of the adjustment.
- j. Adjustments should be based on river sedimentation processes and the various factors affecting these processes. Each adjustment should be based on developments during the preceding tests and the effects of adjustments made during those tests.

8. Base Test

- a. Remold model bed based on latest available survey.
- b. Operate model using typical hydrograph and discharge scale relation and discharge-sediment relation curve developed during final adjustment and verification; maintain stages at same control gage (near center of model) as in the adjustment tests.
- c. Obtain water-surface elevations with all flows and plot water-surface profiles for representative flows. Obtain tailgate settings for each flow.
- d. Repeat reproduction of typical hydrograph until developments in model become reasonably stable or have indicated definite trends in development.
- e. Survey model bed at end of each run.
- f. Evaluate results based on effect of typical hydrograph and accumulative differences between base test and verification test.
- g. Prepare written description of test, results, and conclusions. Start drafting hydrograph and contoured maps for final report.
- h. Develop a rating curve for the gage at the lower end of the model to be used as control gage in tests of improvement plans.

9. Test of Improvement Plan

- a. Install improvement plan.
- b. Remold model bed if results of base test are considerably different from what can be expected at time of construction in the prototype.

- c. Provide for any drastic changes in the alignment and channel cross section that can be anticipated from the improvement plan by molding the bed to conform to the anticipated change to reduce time required for testing. This is particularly important if the plan changes the channel cross-sectional area significantly.
- d. Prepare description and sketch of plan as installed in the model including any changes made in the molded bed because of the plan.
- e. Operate model by reproducing typical hydrograph. Control stages at lower end of model using elevations obtained in the base test for each stage.
- f. Observe model bed during test and record significant developments and effects of low, medium, and high flows.
- g. Survey model bed at end of each run and evaluate results. Do not disturb bed of model at end of run until it has been determined that the test is completed.
- h. Prepare at least a brief written description of the results, evaluation, and conclusions reached. File with description of plan.
- i. Make plan modifications before start of next run if results definitely indicate need for modification or additions to the existing plan. Record description with sketch and state purpose of the change.
- j. Prepare in final form, as soon as practical, results that will be included in final report. Normally only description of plan and end results of the plan need be included in final report.
- k. Prepare narrative description of plan and results of tests for final report as soon as practical after completion of each test. Notes based on preliminary evaluation of test and discussions including modifications proposed for next test and purpose should be prepared before start of next test.
- l. Remolding for the next test will depend on changes in the plan and changes in model bed modified by the previous plans.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Franco, John J

Guidelines for the design, adjustment, and operation of models for the study of river sedimentation problems / by John J. Franco. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.

57, [14] p. : ill. ; 27 cm. (Instruction report - U. S. Army Engineer Waterways Experiment Station ; H-78-1)

1. Alluvial streams. 2. Bed materials (Models). 3. Guidelines. 4. Hydraulic models. 5. Movable-bed models. 6. Sediment transport. 7. Sedimentation. 8. Stream beds. I. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Instruction report ; H-78-1.

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